INTEGRATING ENVIRONMENTAL DATA ACQUISITION AND LOW COST WI-FI DATA COMMUNICATION

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Thesis Prepared for the Degree of

MASTER OF SCIENCE

UNIVERSITY OF NORTH TEXAS

December 2009

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Gurung, Sanjaya. Integrating environmental data acquisition and low cost Wi-Fi data communication. Master of Science (Electrical Engineering), December 2009, 259 pp., 45 tables, 101 illustrations, references, 90 titles.

This thesis describes environmental data collection and transmission from the field to a server using Wi-Fi. Also discussed are components, radio wave propagation, received power calculations, and throughput tests. Measured receive power resulted close to calculated and simulated values. Throughput tests resulted satisfactory. The thesis provides detailed systematic procedures for Wi-Fi radio link setup and techniques to optimize the quality of a radio link.

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ACKNOWLEDGEMENTS

First of all, I would like to take this opportunity to express my gratitude towards Dr. Miguel F. Acevedo for his full support and supervision throughout the two years' time I spent for my entire work. I am very grateful to Dr. Ermanno Pietrosemoli for the brilliant ideas and suggestions he shared with me during the Wi-Fi link setup. I am very much indebted towards him also for his dedication and cooperation in the field work including installation of radio equipment during his visit to the University of North Texas in December 2008. I would also like to thank my committee members Dr. Xinrong Li and Dr. Shengli Fu for their invaluable suggestions and support which helped clear hurdles that I encountered while doing my thesis work.

I would also like to acknowledge my friend Jue Yang, Ph.D. student of Department of Computer Science at University of North Texas who helped me, in every way that a student or researcher can be helped. I wouldn't have been able to advance my thesis work at a good pace without his precious assistance. I would also like to thank my colleagues Chengyang Zhang, Shu Chen, Kalyan Pathapati, Martin Xu and Rakesh Rao for their kind cooperation and active involvement in radio installation at Discovery Park. I am thankful to Carlos Jerez, Rajan Rijal, Vivek Thapa, Dr. Bruce Hunter and Heinrich Goetz for their help during radio installation at Discovery Park and the EESAT building.

I would also like to thank my colleague Mr. Kiran Lamichhane for his extensive support in the network throughput measurement. Last but not least, I would like to thank Dr. Ram Vasudevan for helping me to prepare this thesis. And finally, in case I forgot to mention the names of those people who helped me directly or indirectly n this work, I would like to thank all of them also.

TABLE OF CONTENTS

Page

ACKNOWLEDGEMENTS iii

LIST OF TABLES ix

LIST OF ILLUSTRATIONS xii

LIST OF ACRONYMS xvii

1. INTRODUCTION 1

1.1 Objectives 2

1.2 Hardware Description: (Background) 2

1.3 Motivation 4

1.4 Contribution to the Field 4

1.5 Organization of the Thesis 5

2. WEATHER MONITORING SYSTEM: OVERVIEW 7

2.1 Environmental Monitoring System in Greenbelt Corridor (GBC_WS) 7

2.2 Environmental Monitoring System in Discovery Park 9

3. COMPONENTS OF ENVIRONMENTAL MONITORING SYSTEMS 13

3.1 Weather Station Components 13

3.1.1 Datalogger 13

3.1.2 Environmental Sensors 24

3.1.3 Powering and Charging Devices 35

3.1.4 Optically Isolated RS-232 Interface (SC32B) 41

3.2 Radio Components 43

3.2.1 Nanostation2 43
3.2.2 Ethernet Interface 59
3.2.3 Network Switch 60
4. DATA COLLECTION PROCEDURE 61
4.1 Greenbelt Weather Station (GBC_WS) 61
4.1.1 Functional Overview: Greenbelt Weather Station (GBC_WS) 62
4.1.2 PC208W: Datalogger Support Software for CR10X 64
4.1.3 EDLOG: Programming Editor for CR10X 68
4.2 Discovery Park Weather and Soil Station (DP_WS) 73
4.2.1 Functional Overview of DP_WS 73
4.2.2 LoggerNet 3.4.1: Datalogger Support Software for CR1000 74
4.2.3 CRBasic: Programming Editor for CR10X 82
4.2.4 Inter-connection of Datalogger and Nanostation2 87
5. WI-FI TECHNOLOGY AND RADIO WAVE PROPAGATION THEORY 89
5.1 Wi-Fi Technology: Introduction 89
5.1.1 History: Evolution of Wi-Fi 90
5.1.2 Advantages and Challenges of Wi-Fi 92
5.1.3 Wi-Fi Channels 93
5.1.4 Interference in 2.4 GHz ISM Band 101
5.1.5 Wi-Fi Vs other WLAN Technologies 103
5.1.6 Advantages of Wi-Fi Technology over GPRS Technology 105
5.2 Radio Wave Propagation Theory 107

5.2.1 Types of Radio Waves 109
5.2.2 Phenomenon of Radio Wave Propagation 113
5.2.3 Polarization of Radio Wave 117
5.2.4 Radio Wave Propagation Models 120
5.2.5 Path Loss 127
6. WI-FI RADIO LINK SETUP 137
6.1 Methodology 138
6.2 Field Survey 138
6.3 Technical Design 143
6.3.1 Selection of Propagation Model 143
6.3.2 Channel Selection 146
6.3.3 Radio-Link Modeling 154
6.4 Installation 156
6.5 Configuration Settings 158
6.5.1 EESAT_NS2 Settings 159
6.5.2 DPWS_NS2 Settings 160
6.6 Antenna Alignment 161
7. QUALITY OPTIMIZATION OF A WI-FI RADIO LINK 164
7.1 Causes of Radio-Link Instability 165
7.2 Remedies of Radio-Link Instability 169
7.2.1 Adjustment of Antennas Perfectly 170
7.2.2 Appropriate Settings of Various Parameters 172

7.2.3 Use of Various Diversity Techniques 179
7.2.4 Mounting of Antennas at Sufficient Heights 182
7.2.5 Design of Ample Fade Margin 188
7.2.6 Use of Repeaters 189
8. THROUGHPUT PERFORMANCE MEASUREMENT 192
8.1 Throughput Test Experiments 194
8.1.1 Test for 100 Mbps Cat5 Cable 198
8.1.2 Test for Wireless Router 200
8.1.3 Test for Nanostation2 201
8.2 Throughput Measurement of EESAT_NS2 - DPWS_NS2 Link 207
8.2.1 Throughput Measurements Using Iperf 208
8.2.2 Throughput Measurements Using Network Speed Test Tool 214
8.3 Maximizing the Radio-Link Throughput Performance 220
8.3.1 Various Factors Affecting Throughput Performance 220
8.3.2 Techniques Used to Maximize the System Throughput 221
8.4 Impact of Data Rate on Throughput 223
9. CONCLUSION 226
APPENDIX A 228
EDLOG PROGRAM CODE FOR GBC_WS 228
APPENDIX B 244
CRBASIC PROGRAM CODE FOR DP_WS 244
REFERENCES 249

LIST OF TABLES

Page

3-1. CR10X technical specifications. 18

3-2. CR1000 technical specifications. 23

3-3. 03001 wiring with CR10X and CR1000. 25

3-4. HMP50 wiring with CR10X and CR1000. 26

3-5. CS106 wiring with CR10X and CR1000. 28

3-6. LI200X wiring with CR10X and CR1000. 29

3-7. TE525 wiring with CR10X and CR1000. 31

3-8. EC-5 wiring with CR10X and CR1000. 33

3-9. T4 wiring with CR10X and CR1000. 35

3-10. Technical specifications of PS-12120. 37

3-11. Technical specifications of solar panels. 39

3-12. Technical specifications of charging regulator. 41

3-13. Technical specifications of SC32B. 42

3-14. Technical specifications of Nanostation2. 45

3-15. Data rate vs Rx sensitivity. 46

3-16. Technical specifications of NL120. 59

4-1. PC208W vs LoggerNet. 86

5-1. IEEE standards: Comparison. 91

5-2. 2.4 GHz channel allocation. 95

5-3. Channels allowed in 2.4 GHz band. 96

5-4. Channels allowed in 5 GHz band. 98

5-5. Comparison table: 2.4 GHz Wi-Fi Vs 5 GHz Wi-Fi. 100

5-6. Wi-Fi vs cellular technologies 105

5-7. Wi-Fi vs GPRS technology 106

5-8. Electromagnetic spectrum 109

5-9. Tx power vs RSL for 2.4 GHz. 123

5-10. Path loss vs transmission distance. 130

6-1. Field survey data 142

6-2. Overlapping and non overlapping channels. 148

6-3. Input parameters for modeling. 155

6-4. Output parameters obtained after simulation. 156

6-5. Nanostaion2 configuration settings. 160

8-1. Bandwidth vs throughput 194

8-2. A typical example of an Iperf outputted result window. 196

8-3. Iperf arguments and their purposes. 197

8-4. Throughput Expt. 8.2.1-1: Parameters settings 209

8-5. Throughput Expt. 8.2.1-2: Parameters settings 210

8-6. Throughput Expt. 8.2.1-3: Parameters settings 211

8-7. Throughput Expt. 8.2.1-4: Parameters settings 212

8-8. Throughput Expt. 8.2.2-1: Parameters settings 215

8-9. Throughput Expt. 8.2.2-2: Parameters settings 216

8-10. Throughput Expt. 8.2.2-3: Parameters settings 217

8-11. Throughput Expt. 8.2.2-4: Parameters settings..... 218

8-12. Throughput results of Iperf and network speed tool. 219

8-13. Data rate vs throughput for IEEE802.11g. 224

LIST OF ILLUSTRATIONS

Page

2-1. Greenbelt Weather Station (GBC_WS) 8

2-2. Environmental Monitoring System in Greenbelt Corridor 8

2-3. Discovery Park Weather and Soil Station (DP_WS) 10

2-4. Environmental Monitoring System in Discovery Park 11

3-1. Dataloggers Used in the Field 14

3-2. Wiring Panel of CR10X 15

3-3. Wiring Panel of CR1000 20

3-4. 03001 RM Young Wind Sentry 24

3-5. Air Temperature and RH Sensor and Radiation Shield 26

3-6. CS106 and Its Jumper Setting 27

3-7. LI200X Pyranometer 29

3-8. TE525 Tipping Bucket Rain Gage 30

3-9. EC-5 Soil Moisture Sensor 32

3-10. T4 Tensiometer 34

3-11. 12 V 12 Ahr Sealed Lead Acid Rechargeable Battery 36

3-12. Solar Panels 38

3-13. Charging Regulator Circuit Diagram 40

3-14. SC32B Optically Isolated RS-232 Interface 42

3-15. Nanostation2 44

3-16. Main Page in Station Mode 48

3-17. Link Setup Page in Station Mode 49
3-18. Link Setup Page in Access Point Mode 50
3-19. Network Page in Bridge Mode 51
3-20. Network Page in Router Mode 52
3-21. Advanced Page in Conservative Rate Algorithm Mode 54
3-22. Services Page 56
3-23. System Page 58
3-24. NL120 59
3-25. Network Switch 60
4-1. Functional Overview: Greenbelt Weather Station (GBC_WS) 62
4-2. PC208W Main Window 64
4-3. .CSI Input Program File 68
4-4. Edlog .DLD Program File 69
4-5. Edlog .FSL Program File 70
4-6. ASCII, Comma Separated Input File 71
4-7. ASCII-Printable Input File 71
4-8. Field Formatted ASCII Input File 72
4-9. Functional Overview of DP_WS 73
4-10. PC208W Main Window 75
4-11. Transformer Utility: .CSI to .CR1 Input Files 80
4-12. Transformer Utility: .CSI to .CR1 Output Files 80
4-13. CRBasic .CR1 Input Program File 83

4-14. Normal View-Comma Separated 85
4-15. Expand Tabs View-Field Formatted 85
4-16. Hex View-Hexadecimal Format 86
4-17. Inter-connections of Radio Equipments of DP_WS 87
5-1. 2.4 GHz Wi-Fi Channels 94
5-2. A Pictorial View of 2.4 GHz Technology Applications 102
5-3. Speed Vs Mobility: WLAN Technologies 104
5-4. Electromagnetic Wave Propagation 108
5-5. Radio Waves: Direct Wave and Ground Reflected Wave 112
5-6. Radio Waves: Surface Wave and Sky Wave 112
5-7. Ionospheric Refraction 114
5-8. Vertical Polarization 118
5-9. Horizontal Polarization 118
5-10. Free Space Propagation Model 121
5-11. Tx Power Vs RSL for 2.4 GHz 124
5-12. Two-Ray Propagation Model 125
5-13. Path Loss Vs Transmission Distance 131
5-14. Attenuation Vs Distance 133
6-1. EESAT – DP_WS 137
6-2. Google Map Snapshot of EESAT – DP_WS Link 141
6-3. US 2.4 GHz Channel System 147
6-4. AirView2: A 2.4 GHz Wi-Fi Spectrum Analyzer 149

6-5. DP_WS 2.4 GHz Channel Study (Nanostation2 NOT Connected) 151

6-6. DP_WS 2.4 GHz Channel Study (Nanostation2 Connected)..... 151

6-7. EESAT 2.4 GHz Channel Study (Nanostation2 NOT Connected) 152

6-8. EESAT 2.4 GHz Channel Study (Nanostation2 Connected)..... 153

6-9. Simulation Result of EESAT - DPWS Radio-link Modeling 155

6-10. Nanostations in EESAT and DP_WS..... 158

6-11. Antenna Radiation Pattern..... 162

6-12. Snapshot of DPWS_NS2 Main Page 163

7-1. Disrupted Fresnel Zone 169

7-2. Waste of Energy Due to Improper Antenna Adjustment 170

7-3. Vertical Tilting of Antenna 171

7-4. Data Rate Vs Rx Sensitivity from Table 3-15..... 173

7-5. A 2.4 GHz North American Channel System 176

7-6. Space Diversity Using Two Antennas in Receiver 180

7-7. 1st Fresnel Zone..... 183

7-8. Fresnel Zone being Obstructed in Various Ways..... 184

7-9. Use of a Passive Repeater for Rerouting a LOS Blocked Signal..... 190

7-10. Use of an Active Repeater to Retransmit the Weakened Signal..... 190

8-1. Throughput Test Setup for Cat5 Cable 198

8-2. Throughput Result of Cat5 while Transferring Video File..... 199

8-3. Throughput Test Setup for Wireless Router..... 200

8-4. Throughput Result of Wireless Router while Transferring Video File..... 201

8-5. Throughput Test Setup for Nanostation2 202

8-6. Throughput Result of Experiment 1 203

8-7. Throughput Result of Experiment 2 204

8-8. Throughput Result of Experiment 3 204

8-9. Throughput Result of Experiment 4 205

8-10. Throughput Test Setup for EESAT_NS2-DPWS_NS2 Link 207

8-11. Throughput Result of Experiment 8.2.1-1 209

8-12. Throughput Result of Experiment 8.2.1-2 210

8-13. Throughput Result of Experiment 8.2.1-3 211

8-14. Throughput Result of Experiment 8.2.1-4 212

8-15. Throughput Result of Experiment 8.2.2-1 215

8-16. Throughput Result of Experiment 8.2.2-2 216

8-17. Throughput Result of Experiment 8.2.2-3 217

8-18. Throughput Result of Experiment 8.2.2-4 218

8-19. Data Rate Vs Throughput for IEEE802.11g 224

LIST OF ACRONYMS

AAP	Adaptive antenna polarity
ASCII	American Standard Code for Information Interchange
BASIC	Beginner's All-purpose Symbolic Instruction Code
Cat.5	Category 5
CCK	Complementary code keying
CDMA	Code division multiple access
CRI	Computing research infrastructure
DECT	Digital European cordless telephone
DHCP	Dynamic Host Control Protocol
DIFF	Differential
DP_WS	Discovery Park Weather Station
DPWS_NS2	Discovery Park Weather Station Nanostation2
DSSS	Direct sequence spread spectrum
EESAT	Environmental Education, Science and Technology
EESAT_NS2	Environmental Education, Science and Technology Nanostation2
EHF	Extremely high frequency
ELF	Extremely low frequency
ESSID	Extended Service Set Identification
EWMA	Exponentially weighted moving average

FCC	Federal Communications Commission
FSL	Free space loss
GBC_WS	Greenbelt Corridor Weather Station
GPRS	General packet radio service
GPS	Global positioning system
GSM	Global system for mobile communications
HF	High frequency
Hi-Fi	High fidelity
HTTP	Hypertext Transfer Protocol
HTTPS	Hypertext Transfer Protocol Secure
ICMP	Internet Control Message Protocol
IEEE	Institute of Electrical and Electronics Engineers
IP	Internet Protocol
ISM	Industrial, scientific and medical
Kbps	Kilo bits per second
KBps	Kilo bytes per second
LAN	Local area network
LF	Low frequency
LOS	Line of sight
MAC	Media access control
Mbps	Mega bits per second
MBps	Mega bytes per second

NFC	Near field communication
NHC	Natural Heritage Center
OFDM	Orthogonal frequency division multiplexing
OSI	Open System Interconnection
PSD	Power spectral density
RH	Relative humidity
RSL	Receive signal level
RTMC	Real time monitor and control
RTMC-Dev	Real time monitor and control -Development
RTMC-RT	Real time monitor and control -Run Time
RTS	Request-to-send
SBC	Single board computer
SCADA	Supervisory control and data acquisition
SDI	Serial data interface
SE	Single ended
SHF	Super high frequency
SNMP	Simple Network Management Protocol
SNR	Signal-to-noise ratio
SSID	Service set identification
SWAP	Shared Wireless Access Protocol
TCP/IP	Transmission Control Protocol/Internet Protocol
UDP	User Datagram Protocol

UHF	Ultra high frequency
UMTS	Universal mobile telecommunication system
UNT	University of North Texas
UTP	Unshielded twisted pair
UV	Ultraviolet
UWB	Ultra wide band
VHF	Very high frequency
VLF	Very low frequency
VWC	Volumetric water content
WDS	Wireless distribution system
WEP	Wired equivalent privacy
Wi-Fi	Wireless fidelity
WiMAX	Worldwide Interoperability for Microwave Access
WLAN	Wireless local area networking
WPA	Wi-Fi protected access
WRAN	Wireless regional area networks

CHAPTER 1

INTRODUCTION

Real time environmental monitoring is the process of collecting environmental data of a particular area by deploying an automated station where different kinds of environmental sensors are connected. Environmental parameters such as wind speed and wind direction, rainfall, solar radiation, air pressure, air temperature, relative humidity etc. can be measured with the help of those sensors deployed in the field.

The present thesis is based on the field work carried out at Greenbelt Weather and Soil Station (GBC_WS hereafter) located at the Greenbelt Corridor of the Ray Roberts State Park, Denton, and Discovery Park Weather and Soil Station (DP_WS hereafter) at the University of North Texas (UNT hereafter), Denton during January 2008 - October 2009. The thesis provides a comprehensive description of the various steps involved, i.e., data collection, and transfer of data. This work includes data collection procedure, transferring of data from one data collection unit (datalogger) to another, and finally transmitting all those combined collected data to a web server using wireless fidelity (Wi-Fi hereafter) technology, where, once processed is made available for public access via internet.

This thesis presents an alternative method to the costly general packet radio service (GPRS hereafter) solution, which has been used for transmitting data from the GBC_WS to the computing research infrastructure (CRI hereafter) web server. An innovative, low cost and a high data rate Wi-Fi technology is employed to transmit the collected data from the weather station in the field to the web server. Since the new Wi-Fi technology replaces the GPRS network, service charge doesn't have to pay service charge for the new system deployed in DP_WS, thus cutting down the cost of transmission. Wi-Fi technology operates in an unlicensed frequency band and hence its use is free.

1.1 Objectives

- Deploy a weather and soil monitoring system to collect environmental data from the field
- Improve the data transmission quality of service by implementing a low cost and high data rate unlicensed Wi-Fi technology

1.2 Hardware Description: (Background)

This section includes a brief description of the hardware components used in this work. An automated station deployed in a particular area collects environmental data. A typical weather station comprises various devices. A datalogger is a programmable electronic device that records environmental data from various kinds of environmental sensors. Its main functions are data

collection and storage. The datalogger used in this work is a product of Campbell Scientific Inc.

Sensors, wired with the datalogger, are the other important components of the station. They measure environmental parameters such as air temperature, air pressure, wind speed and wind direction, rainfall, solar radiation, relative humidity, soil moisture, etc. The remaining components relate to power supply: battery, solar panel, charging regulator etc. The datalogger, battery and charging regulator are contained inside a weatherproof enclosure, while all the environmental sensors and solar panel remain outside of the enclosure.

In order to transmit the collected data to the server, a Wi-Fi link is established using a Nanostation2, which is a radio equipment manufactured by Ubiquity Networks and operates at 2.4 GHz. It has a built-in directional antenna, which radiates the signal in line of sight (LOS) direction. Two Nanostation2 devices were installed, one at each site. At the weather station (data collection site) and the base site (where there is an internet access). By linking these two sites via Nanostation2 link, the data collected by weather station are sent to the system server.

An ethernet interface allows connecting the datalogger and the Nanostation2. This interface allows the datalogger to communicate over a local network or a dedicated internet connection via Transmission Control Protocol/Internet Protocol (TCP/IP here after) [1].

1.3 Motivation

Before the implementation of this new Wi-Fi technology in the project, GPRS network has been used and hence has been paid for its services to transmit the data to the CRI web server. The plan was to directly transmit the data from the field to the server, and reduce cost substantially. In addition, the typical data throughput of GPRS network is around 15 -40 K bps while its maximum data rate is 171.2 Kbps [2-4]. This is much lower than the Wi-Fi technology, which is being used now.

Wi-Fi technology fits both in quality transmission and in cost effectiveness for the application that this thesis talks about. With Wi-Fi technology, one can achieve greater data throughput and radio-link stability; therefore this technology is selected this for implementing the link at the DP_WS.

1.4 Contribution to the Field

Using the Wi-Fi technology resource, a high-speed radio link has been established for transmitting the environmental data from the field to the server. This avoids the necessity of paying for any third party for using their services such as GPRS network. This thesis offers guidelines of the techniques to implement similar kind of projects; for example, developing wireless internet service in remote and rural areas especially in developing countries.

1.5 Organization of the Thesis

Chapter 2 is an overview of weather monitoring system with its functional block diagram. The overview includes the two systems: the GBC_WS and the DP_WS. However, the latter is described in more detail because this thesis focuses on this station for the implementation of Wi-Fi technology.

Chapter 3 deals with the detailed description of all the components of the weather monitoring system with the wirings of all the sensors used in this project and their core functions.

Chapter 4 deals with the data collection procedure from the field. In this chapter, a functional overview, datalogger support software, and datalogger programming are discussed.

Chapter 5 discusses Wi-Fi technology, its advantages and challenges. It also describes radio wave propagation theory focusing on the free space propagation model and free space loss. This chapter also discusses some advantages of Wi-Fi technology over GPRS technology for this application.

Chapter 6 deals with the detailed description of the Wi-Fi link set up between (Environmental Education, Science and Technology (EESAT)) building of the UNT and DP_WS. It also introduces radio-link modeling software used to pre-assess the link quality and a Wi-Fi spectrum-analyzer tool known as AirView2 for choosing the appropriate channel.

Chapter 7 describes various techniques for Wi-Fi link quality optimization. It also includes received power calculation, comparison of results using different

approaches such as theoretical calculation, radio mobile software and Nanostation2 built in tool. Also discussed is the importance of Fresnel zone calculation for optimizing the link quality.

Chapter 8 deals with the various throughput tests using the Iperf tool and Nanostation2 Network Speed tool, and analysis of their results. This chapter also discusses some techniques to improve the throughput of the link established between DP_WS and EESAT.

Chapter 9 concludes the thesis with a summary and providing guidelines for possible future extensions of this work.

CHAPTER 2

WEATHER MONITORING SYSTEM: OVERVIEW

Work has been done in two weather and soil monitoring systems (GBC_WS and DP_WS). Each one consists of an environmental data collecting electronic device known as datalogger, environmental sensors, powering equipments like battery, charging device such as solar panel and a charging regulator. The datalogger, pressure sensor, battery and charging regulators are inside an enclosure mounted on a tripod. Except the barometric pressure sensor, all other environmental sensors and solar panels are outside the enclosure.

2.1 Environmental Monitoring System in Greenbelt Corridor (GBC_WS)

The GBC_WS is located in the midst of the forest of Greenbelt Corridor State Park situated at US-380, Denton, TX-USA. The UNT ECOPLEX project deployed the system in 2004. Figure 2-1 is the picture of GBC_WS taken on September 2009. The main objective was to monitor different kinds of environmental phenomena by measuring different weather parameters such as air temperature, air pressure, relative humidity, rainfall, wind speed and wind direction, solar radiation etc and the soil moisture around the weather station. Figure 2-2 shows the functional block diagram of GBC_WS.

Figure 2-1 Greenbelt Weather Station (GBC_WS)

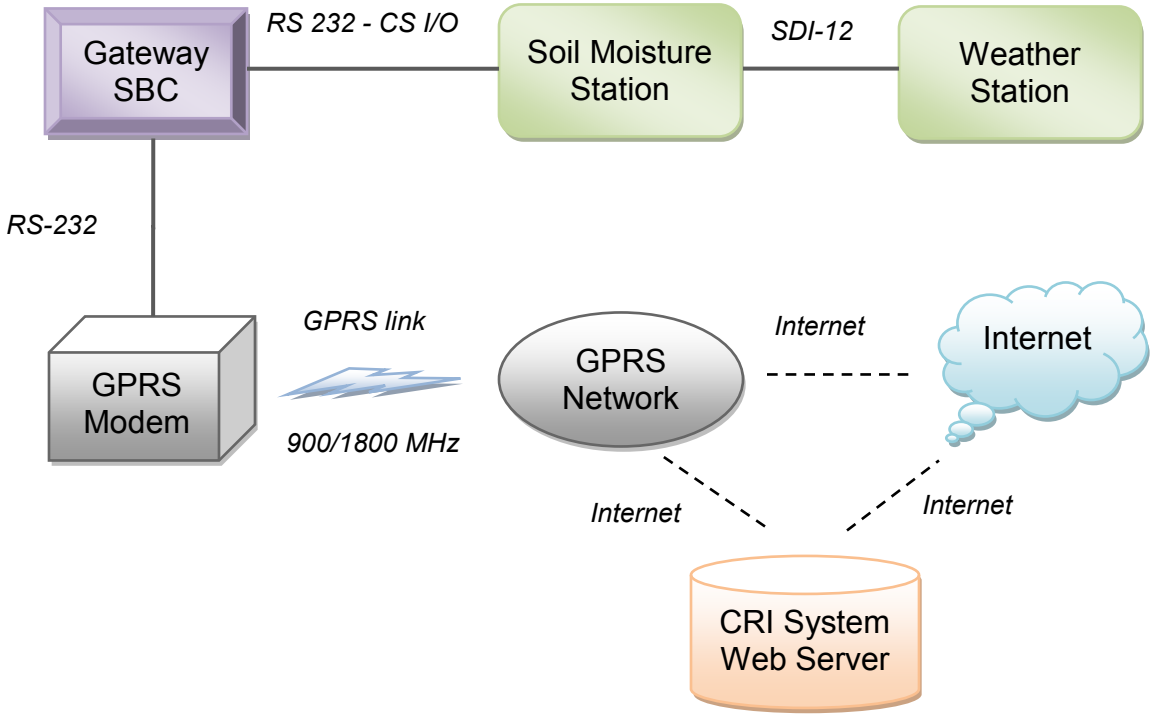


Figure 2-2 Environmental Monitoring System in Greenbelt Corridor

There are two systems in GBC_WS. One station measures weather parameters like air temperature, relative humidity, air pressure, wind speed and direction, solar radiation, and rainfall. The other station is for measuring soil moisture and soil pressure around the station. For the sake of simplicity, they will be referred to as weather station and soil moisture station respectively.

There is a datalogger in each station for collecting and storing data. The data are collected at an interval of 15 minutes. The weather station datalogger and soil moisture datalogger connect by wire with each other and the program is written in such a way that once the data are collected in both of the dataloggers, the data of weather station are transferred to the soil moisture station. A single board computer (SBC hereafter) acts as an interface between the GBC weather station and CRI web server. To be more specific, it acts as a bridge between the datalogger and the GPRS modem. Then those collected data are transmitted to GPRS network via a GPRS modem, which operates at 900/1800 MHz. The modem forwards the data to the CRI system web server where they are processed, refined and finally made accessible to public via internet.

2.2 Environmental Monitoring System in Discovery Park

The DP_WS is located at Discovery Park of UNT situated in Denton, Texas, USA. The system was deployed in October, 2008 by the CRI Project Team of UNT. Figure 2-3 is the picture of DP_WS taken on June 2009. The main objective was to set up a test bed for the project as well as to monitor environmental conditions by measuring different weather parameters like air

temperature, air pressure, relative humidity, rainfall, wind speed and wind direction, and solar radiation; and also the soil moisture around the weather station. The block diagram of the environmental monitoring system of DP_WS is shown below in Figure 2-4. The DP_WS, installed in a tree-less area, counts with sufficient solar energy to power the system. Consequently, the environmental infrastructure of DP_WS is somewhat different from that of GBC_WS, where there is tree cover all the way around. The functional block diagram of DP_WS is shown below in Figure 2-4.

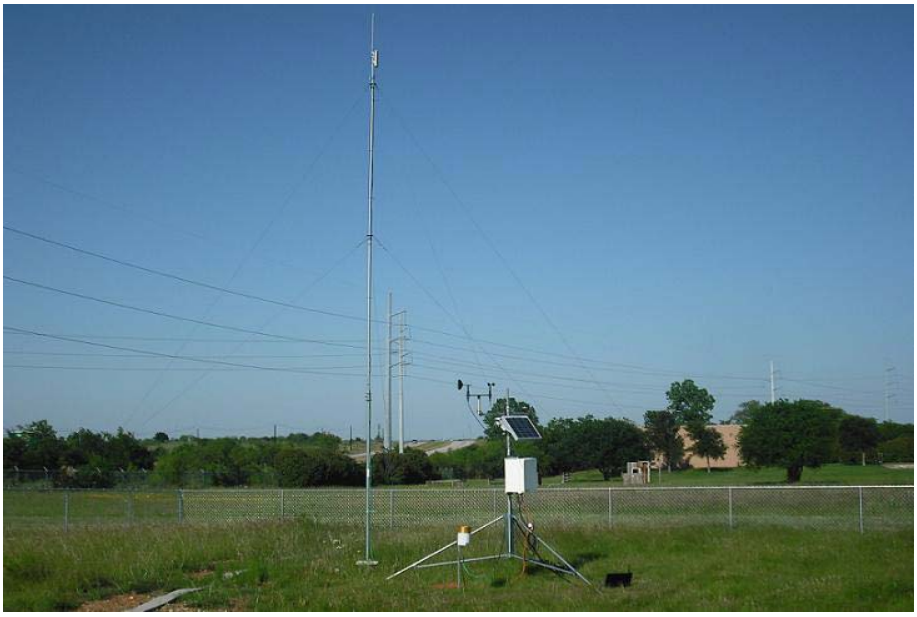


Figure 2-3 Discovery Park Weather and Soil Station (DP_WS)

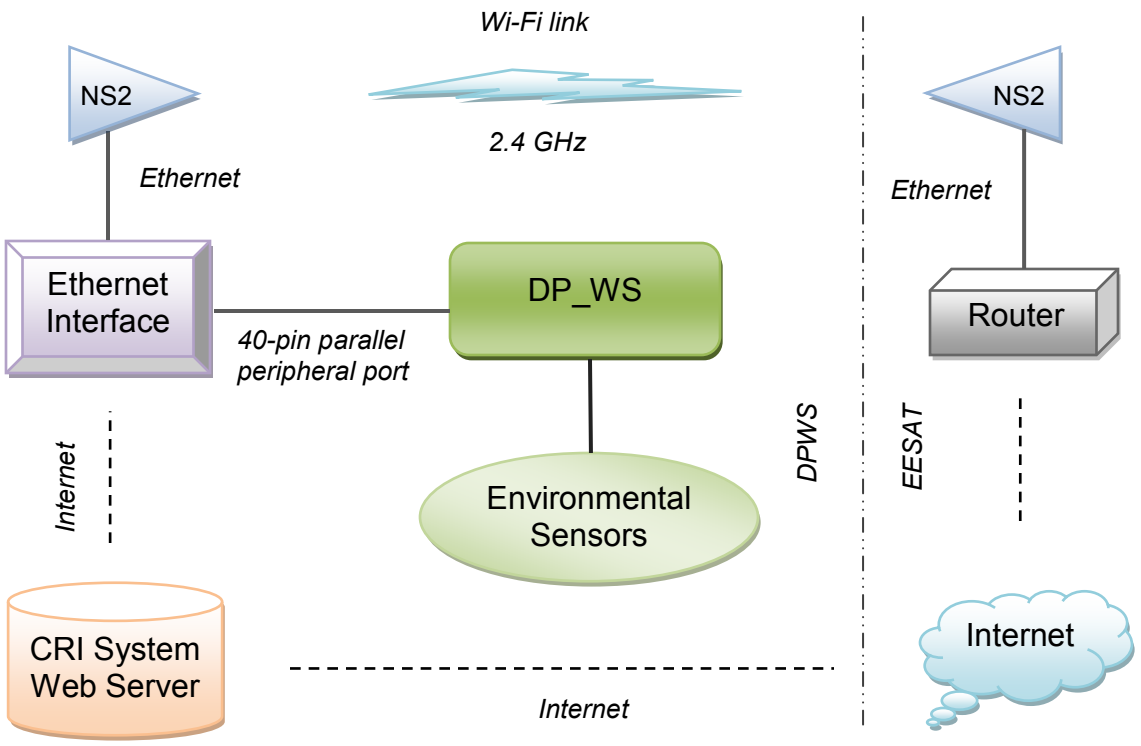


Figure 2-4 Environmental Monitoring System in Discovery Park

All the environmental sensors are deployed in a single weather station. As in the previous case, the data collected via environmental sensors are stored in the datalogger. However, at DP_WS there is no need to transfer data between dataloggers because it has only one datalogger collecting the environmental data and the station will be using an ethernet interface instead of a SBC. But the main difference between GBC_WS and DP_WS is that DP_WS uses Wi-Fi technology to transmit the data to the CRI system web server instead of using GPRS. The Ubiquity Networks product named Nanostation2 links DP_WS and the internet.

The Nanostation2 is installed at the top of a 9 m tall pole. Another Nanostation2 is installed at the top of EESAT building of UNT and connected

with an internet source. These two nanostations are installed facing each other so that they are in a line of sight (LOS hereafter) as shown in above Figure 2.4. Because the antenna inside the Nanostation2 is directional, the direct wave is the one which is of matter of concern and so both of the nanostations should be visible to each other or in other words there should not be any obstruction in the LOS path. The more detailed description of Nanostation2 is given in Chapter 3. Once both of the nanostations are installed properly so that they lie along the LOS path, the link could be established after powering them and configuring some settings. The detailed description of the link set up is given in Chapter 6.

CHAPTER 3

COMPONENTS OF ENVIRONMENTAL MONITORING SYSTEMS

The environmental monitoring system consists of various components. For the present work, these all components fall under two different categories: i) weather station components and ii) radio components. This section contains a description of all of these components.

3.1 Weather Station Components

3.1.1 Datalogger

A datalogger is an electronic programmable instrument or device that records environmental data over time via its built in or external sensors. It is generally powered by a lead acid rechargeable battery, which is recharged by an AC adapter wherever available, and by a solar panel. Generally, they are small and hence portable. It has an internal memory for data storage and is based on a digital processor. Dataloggers come in two types. The first type of dataloggers needs a PC for activating, downloading software, viewing and analyzing the collected data. The second type of dataloggers has a local interface device and can be used as a stand-alone device. Between the above-mentioned two types of dataloggers, the first type has been used because these are appropriate for recording data automatically and continuously from the environment once deployed and activated in the field. Campbell Scientific dataloggers of CR10X

and CR1000 series are used in this work. Pictures of typical CR10X and CR1000 dataloggers are given below.

i) CR10X ii) CR1000

Figure 3-1 Dataloggers Used in the Field

a) CR10X

It is a fully programmable datalogger with a non volatile memory widely used in meteorological research, routine weather measurement applications and other kinds of network applications. Upon activation, it can be left unattended in the field to continuously record data over time. It performs a high-resolution 13-bit A/D conversion. A detachable keyboard display that can be carried to multiple stations can be connected via its CS I/O serial port. Running any compatible datalogger support software on the PC connected to CR10X, the program can be written in a program editor called Edlog and downloaded to CR10X. It has internal memory of 128 Kbytes SRAM (available optional memory up to 2 Mbytes) which is nearly equivalent to 60,000 data points [5]. A picture of a typical CR10X is shown above in Figure 3-1(i).

Wiring Panel

Wiring panel is a panel which provides terminals for connecting sensors, power and communication devices. It also incorporates protection against lightning. CR10X has various input/output ports, power and ground terminals etc. To power the datalogger, the voltage level required is 12 V DC but it can intake voltages within the range of 9.6-16 V [5]. A picture showing terminals and I/O ports of CR10X wiring panel is given below in Figure 3-2.

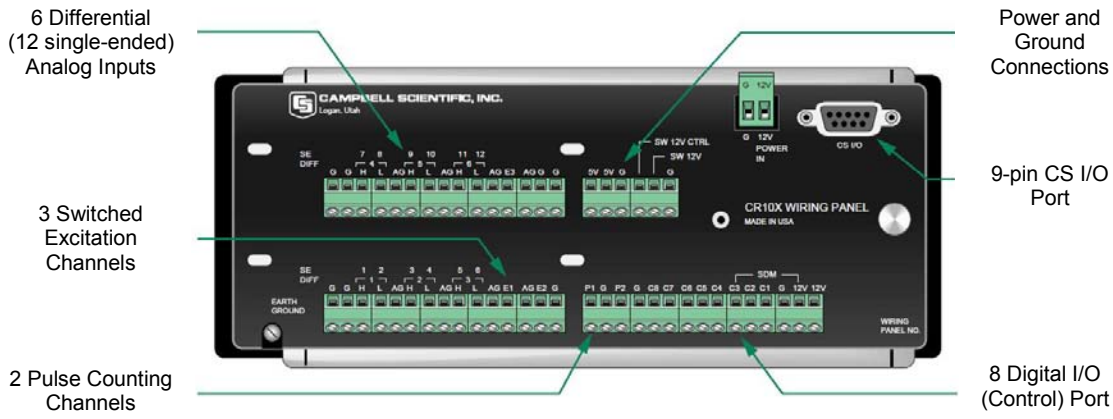

6 Differential (12 single-ended) Analog Inputs
3 Switched Excitation Channels
2 Pulse Counting Channels
Power and Ground Connections
9-pin CS I/O Port
8 Digital I/O (Control) Port
CAMPBELL SCIENTIFIC, INC.
CR10X WIRING PANEL
MADE IN USA

Figure 3-2 Wiring Panel of CR10X

There are a 12 V and a power ground (G) terminals used to supply 12 V DC power to the CR10X datalogger via external 12 V battery. The G terminals are directly connected to the Earth terminal. The terminals labeled 1H to 6L are analog inputs. H refers to high input and L refers to low input for differential channels. So there are altogether 6 high and 6 low differential input channels [5]. For single-ended measurements, either H or L can be used as an independent

channel to measure voltage with respect to AG (Analog Ground) of CR10X. So there are altogether 12 single-ended channels starting sequentially from 1H, 1L, 2H,...5L, 6H, 6L. That means the H and L terminals of differential channel 1 are single-ended channels 1 and 2 respectively. The terminals labeled E1, E2 and E3 are switched excitation outputs used to supply programmable excitation voltages for resistive bridge measurements. The terminals P1 and P2 are the pulse counter channels. Terminals labeled as C1, C2,….,C8 are the digital input/output ports. They are also called control ports. There are two 5 V outputs used to power some external sensors that require 5 V power supply. The switched 12 V outputs can be used to power sensors and devices which require an unregulated 12 V. There is one 9-pin serial I/O port used for communication between CR10X and external devices such as PC, printers and other compatible serial devices [5].

CR10X Operating Systems

The default operating system loaded on CR10X is the Array-Based Operating System unless another is specified at the time of ordering it. Available operating systems for CR10X are:

- Mixed-array operating system (standard): Contains 48 measurement instructions, 52 processing/math instructions, and 20 program control instructions [5].

- Table data operating system (OS10XTD/U): Allows the CR10X to store the final storage data in the form of a table [5].
- PakBus table data operating system (OS10XPB/U). Allows the CR10X to communicate with CR200-series dataloggers in the same network. Final storage data are stored in table format [5].
- Modbus operating system (OS10XMB/U): Supports Modbus protocol allowing the CR10X to interface with supervisory control and data acquisition (SCADA) and MMI software packages. Some earlier CR10X operating systems (OS10X versions older than 1.3) included Modbus in the standard operating systems [5].
- OS10X ALERT operating system: Allows the CR10X to store and transmit data in the ALERT format (flood warning system) [5].

SDI-12

SDI-12 is the acronym for "serial data interface at 1200 baud" It is a standard communication protocol allowing connection of multiple sensors to an SDI-12 compatible datalogger. SDI-12 sensors connect to control ports C1–C8 of CR10X. It communicates using a cable containing 3 wires; a 12 V line, a ground line and a serial data line [5]. SDI-12 can also be used to connect two CR10X dataloggers for making it possible to communicate between the two dataloggers. Once they are connected via SDI-12 interface, the program transfer, data transfer etc. between them is possible.

Table 3-1 CR10X technical specifications.

FEATURE	SPECIFICATION
Voltage	9.6 - 16 Vdc (optimum 12 V)
Current drain	Quiescent - 1.3 mA Processing - 13 mA Active - 46 mA
Analog inputs	12 Single Ended, 6 Differential
Digital/Control ports	8 I/Os (C1 - C8)
Pulse Counter channel	2 (P1, P2)
Communication port	1 CS I/O
Data Storage	Internal memory - 128 Kbytes SRAM (available up to 2 Mbytes)
Input Voltage range	±2.5 V
Switched voltage output	two 12 V
Other voltage output	two 5 V and two 12 V
Scan rate	64 Hz
A/D conversion	13-bits
Switched volt excitation channel	3 (E1, E2 & E3)
Programming	Edlog
Datalogger support software	PC208W, LoggerNet 2.x, PC400
Operating systems	Mixed Array, Table, PakBus, Modbus, ALERT
Communication protocol	Modbus, ALERT
Standard Temperature Range	-25ºC - +50ºC
Dimension	7.8” × 3.5” × 1.5”
Weight	2 lbs

b) CR1000

Like CR10X, it is also a fully programmable datalogger with a non volatile memory. It is a new product of Campbell Scientific Inc. designed especially for replacing the old CR10X to add, upgrade and improve some of the features of CR10X. It is also widely used in meteorological research, routine weather measurement applications and other kinds of network applications. It is also designed for unattended network applications.

It has a high-resolution 13-bit A/D conversion with higher speed of scan rate of 100 Hz. CR1000 is compatible with various datalogger support software like LoggerNet3.x. PC400 1.2, ShortCut 2.2 etc. The program can be written and compiled in a program editor called CRBasic. Facilitating more storage, it has an internal memory of 2 Mbytes SRAM and available optional memory extends up to 4 Mbytes. Instead of ±2.5 V, it has ±5 V input range allowing the sensors output of 5 V without the use of voltage divider. For communication with other external devices, in addition to CS I/O serial port, it also offers two other additional different ports; an RS-232 serial port and a 40-pin parallel peripheral port. CR1000 comes up with processing speed 4 times faster than that of retired CR10X [6]. A picture of a typical CR1000 is shown above in Figure 3-1(ii).

Wiring Panel

CR1000 has various input/output ports, power and ground terminals etc. To power the datalogger, the voltage required is 12 V DC but it can intake

voltages within the range of 9.6-16 V [6]. A picture showing terminals and I/O ports of CR1000 wiring panel is given below in Figure 3-3.

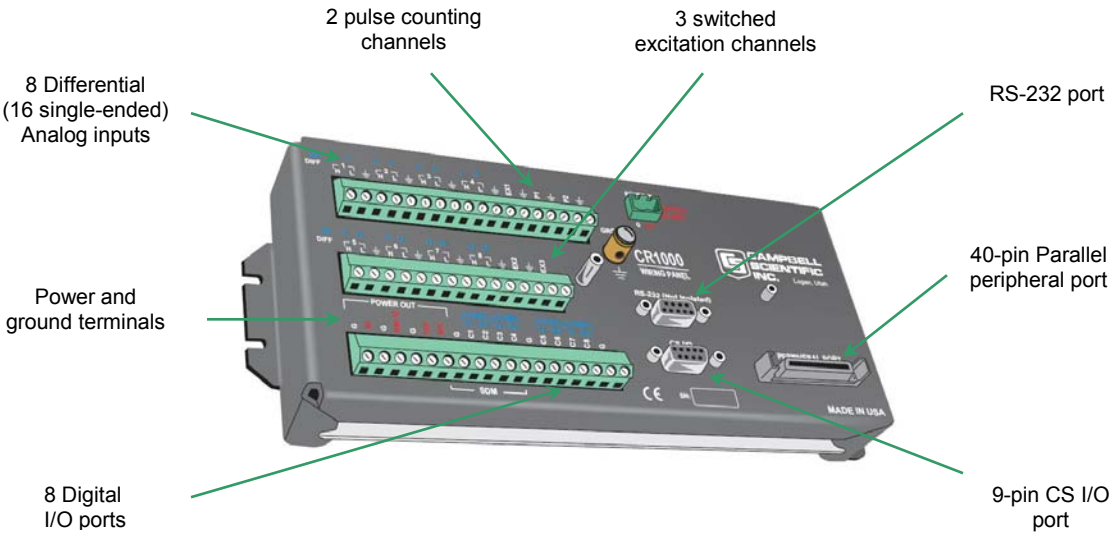


Figure 3-3 Wiring Panel of CR1000

In CR1000 wiring panel also, there is a 12 V and a power ground (G) terminals used to supply 12 V DC power to the datalogger via external 12 V battery. The terminals labeled 1H to 8L are analog inputs. H refers to high input and L refers to low input for differential channels. So there are altogether 8 high and 8 low differential input channels. For single-ended measurements, H or L, either of them can be used as an independent channel to measure voltage with respect to analog ground of CR1000. So there are altogether 16 single-ended channels starting sequentially from 1H, 1L, 2H,...7L, 8H, 8L. That means the H and L terminals of differential channel 1 are single-ended channels 1 and 2 respectively. The terminals labeled VX1, VX2 and VX3 are switched excitation

outputs used to supply programmable excitation voltages for resistive bridge measurements. P1 and P2 terminals are the pulse counter channels. They are also called control ports. There is one 5 V output used to power some external sensors that require 5 V power supply. The switched 12 V outputs can be used to power sensors and devices which require an unregulated 12 V. For communication between CR1000 and its external devices such as PC, printers and other compatible serial and parallel devices, the CR1000 wiring panel is incorporated with a 9-pin serial CS I/O, an RS-232 port and a parallel peripheral port. The peripheral port here can be used to connect Ethernet devices such as NL115. Terminals labeled as C1, C2,….,C8 are the digital input/output ports. In addition to communicating via its RS-232 and CS I/O ports, the CR1000 can also communicate via the digital I/O COM ports [6].

CR1000 Operating Systems

The default operating system loaded on CR1000 is PakBus Operating System unless another is specified at the time of ordering it. Available operating systems for CR1000 are:

- PakBus table data operating system: This operating system uses a packet based communication which creates final storage tables to logically separate different types of data collection such as hourly, daily etc. This protocol allows the CR1000 to communicate with other CR1000 dataloggers in the same network [6].

- Modbus operating system: This operating system supports Modbus protocol (one of the more primitive protocols) allowing the CR1000 to interface with SCADA and MMI software packages. It allows the remote setting of control ports and reading/changing of memory locations [6].

SDI-12

SDI-12 is the acronym for "serial data interface at 1200 baud" It is a standard communication protocol allowing connection of multiple sensors to an SDI-12 compatible datalogger. SDI-12 sensors connect to control ports C1, C3, C5 and C7 of CR1000. It communicates using a cable containing 3 wires; a 12 V line, a ground line and a serial data line [6].

Table 3-2 CR1000 technical specifications.

FEATURE	SPECIFICATION
Voltage	9.6 - 16 Vdc (optimum 12 V)
Current drain	0.6 mA (Sleep mode) 1-16 mA (w/o RS-232 comm.) 17-28 mA (w/RS-232 comm.)
Analog inputs	16 Single Ended, 8 Differential
Digital/Control ports	8 I/Os (C1 - C8) or 4 RS-232 COM
Pulse Counter channel	2 (P1, P2)
Communication port	1 CS I/O, 1 RS-232, 1 parallel peripheral port
Data Storage	Internal memory - 2 Mbytes SRAM (available up to 4 Mbytes)
Input Voltage range	±5.0 V
Switched voltage output	one 12 V
Other output voltage	one 5 V and two 12 V
Scan rate	100 Hz
A/D conversion	13-bits
Switched volt excitation channel	3 (VX1, VX2, VX3)
Programming	CRBasic
Datalogger support software	LoggerNet 3.4.x, PC400, etc.
Operating system	PakBus
Communication protocol	PakBus
Standard Temperature Range	-25ºC - +50ºC
Dimension	9.4” × 4.0” × 2.4”
Weight	2.1 lbs

3.1.2 Environmental Sensors

Environmental sensors are the electronic components to measure physical quantities of environment such as light intensity, air temperature, soil moisture etc. and convert them into signals that can be easily read by an observer. There are many environmental sensors used for measuring different environmental phenomena, but only some of them are used in this project and discussed here in this section.

a) Wind Speed and Direction Sensor

For measuring wind speed and wind direction, 03001 RM Young Sentry is used. A typical 03001 RM Young Sentry is shown in below Figure 3-4. It can be mounted directly to the mast or to the cross arm as shown in above figure. It can measure the wind speed within the range of 0-112 mph and wind direction 360º mechanical and 355º electrical. The temperature range within which it can operate is -50º to +50ºC [7].

Figure 3-4 03001 RM Young Wind Sentry

Wind speed sensor has 3 wires: black, white and clear used for wind speed signal, wind speed reference and wind speed shield respectively. Similarly, wind direction has 4 wires: red, black, white and clear used for wind directional signal, wind direction excitation, wind direction reference and wind direction shield respectively. The connections of the sensor to CR10X and CR1000 dataloggers are shown below in Table 3-3 [7].

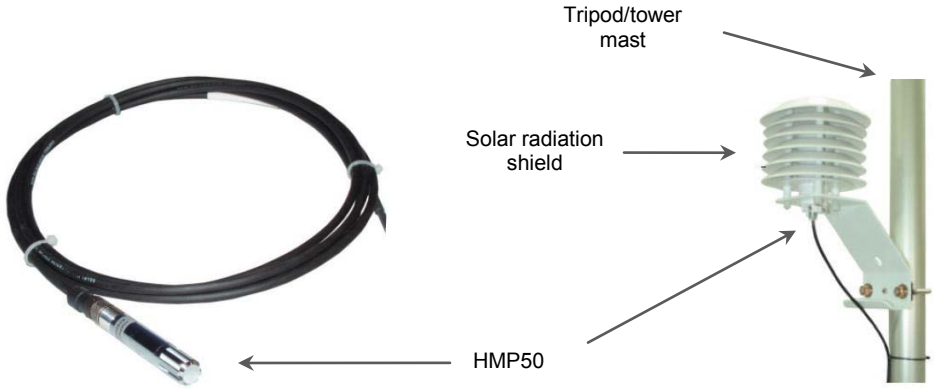
Table 3-3 03001 wiring with CR10X and CR1000.

	WIRE COLOR	DESCRIPTION	CR10X	CR1000
Wind Speed	Black	Wind speed signal	Pulse	Pulse
	White	Wind speed reference	G	⏚
	Clear	Wind speed shield	G	⏚
Wind Direction	Red	Wind direction signal	SE Analog	SE Analog
	Black	Wind direction excitation	Excitation	Excitation
	White	Wind direction reference	AG	⏚
	Clear	Wind direction shield	G	⏚

b) Air Temperature and Relative Humidity Sensor

The Vaisala temperature and relative humidity (RH hereafter) sensor (HMP50) is used for measuring air temperature. A typical HMP50 is shown below in Figure 3-5 (i). When it is installed outdoor or exposed in sunlight, it must be housed in a solar radiation shield which can be mounted directly to the tripod or tower mast as shown in above Figure 3-5 (ii). It can measure air temperature within the range -25º to +60ºC and relative humidity within the range of 0 to 98%.

The typical supply voltage is 12 V but it can intake any voltage within the range of 7 to 28 V DC. And typical current consumption is as low as 2 mA [8].



i) HMP50 ii) 41303 6-plate Gill Solar Radiation Shield

Figure 3-5 Air Temperature and RH Sensor and Radiation Shield

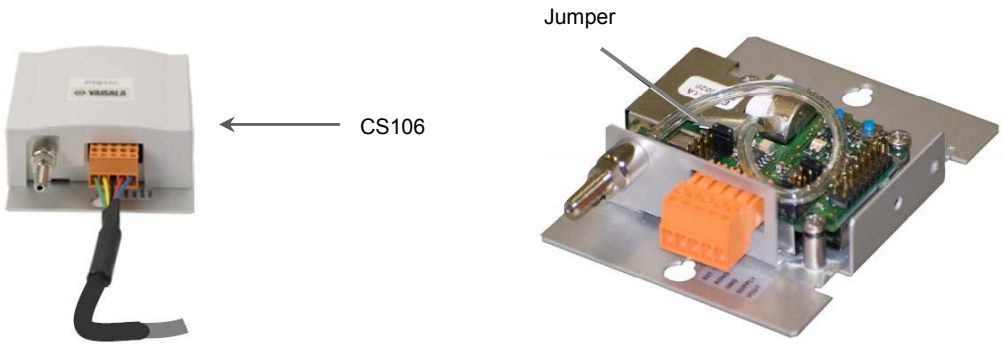
HMP50 has 5 wires: black, white, blue, brown and clear used for temperature, relative humidity, signal and power reference, power and shield respectively. Its connections to CR10X and CR1000 dataloggers are shown below in Table 3-4 [8].

Table 3-4 HMP50 wiring with CR10X and CR1000.

DESCRIPTION	COLOR	CR10X	CR1000
Temperature	Black	SE3	SE1
Relative Humidity	White	SE4	SE2
Signal and power reference	Blue	G	G
Power	Brown	12 V	12 V
Shield	Clear	G	⏚

c) Barometric Pressure Sensor

The Vaisala PTB110 barometer (CS106) is used for measuring atmospheric air pressure. A typical CS106 is shown below in Figure 3-6 (i). It can measure air pressure within the range 500 mb to 1100 mb operating under the temperature range of -40º to + 60ºC. It can operate under a supply voltage between 10 to 30 V but the nominal is 12 V DC. A typical current consumption is about 4 mA during active period and less than 1 µA during quiescent period [9].



i) CS106 i) CS106 jumper setting

Figure 3-6 CS106 and Its Jumper Setting

CS106 has 6 wires: blue, yellow, red, black, green and clear used for pressure (Vout), signal ground (AGND), 12 V supply, power ground (GND), control port or excitation channel and shield (G) respectively. Its connections to CR10X and CR1000 dataloggers are shown below in Table 3-5. The CS106 can be operated in two modes: shutdown and normal. The mode can be selected by

configuring setting of the jumper located underneath the plastic cover of the barometer. When the jumper is not installed, the CS106 is in shutdown mode and the datalogger turns it on and off with a control port or excitation channel. When the jumper is installed, the CS106 is in normal mode and powered continuously. The picture of CS106 shown in Figure 3-5 (ii) is set to shutdown mode [9].

Table 3-5 CS106 wiring with CR10X and CR1000.

DESCRIPTION	COLOR	SINGLE-ENDED		DIFFERENTIAL	
		CR10X	CR1000	CR10X	CR1000
Pressure	Blue	SE7	SE7	4H	4H
Signal ground	Yellow	AG	⏚	4L	4L
Power supply	Red	12 V	12 V	12 V	12 V
Power Ground	Black	G	G	G	G
Control or Excitation	Green	Control port	Control port	Control port	Control port
Shield	Clear	G	⏚	G	⏚

d) Solar Radiation Sensor

LI-COR pyranometer (LI200X) measures solar radiation. Its operating temperature range is -40º to + 65ºC. This sensor is suitable only for day light spectrum, so it can't be used under vegetation or artificial light. It is calibrated only for daylight (400 nm to 1100 nm of light wavelength). Current consumption of LI200X solar radiation sensor is proportional to the incoming solar radiation. A. LI200X should be mounted such that it is never shaded by anything like tower, tripod or any other instruments. For accurate measurement, the LI200X should

be mounted using LI2003S Li-COR leveling base [10]. A picture of a typical LI200X pyranometer is shown in Figure 3-7.

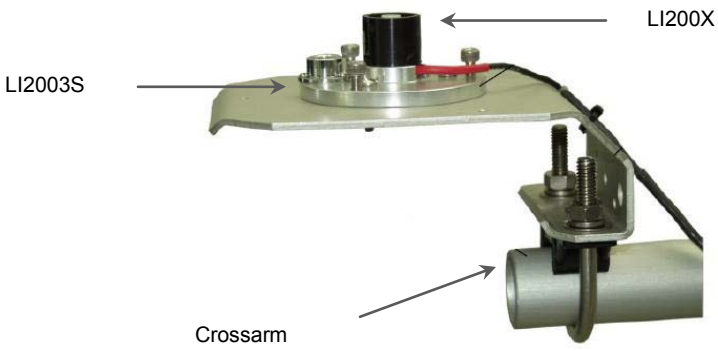


Figure 3-7 LI200X Pyranometer

LI200X has 4 wires: red, black, white and clear used for signal, signal reference, signal ground and shield respectively. Its connections to CR10X and CR1000 dataloggers are shown below in Table 3-6 [11].

Table 3-6 LI200X wiring with CR10X and CR1000.

DESCRIPTION	COLOR	CR10X	CR1000
Signal	Red	1H	1H
Signal reference	Black	1L	1L
Signal ground	White	AG	⏚
Shield	Clear	G	⏚

e) Rain Gage

TE525 tipping bucket rain gage is used for measuring rainfall. Its operating temperature range is 0º to 50ºC. This sensor is factory calibrated and it is not recommended to calibrate again in the field. The rain gage should be mounted at least 30 cm above the ground. The ground surface where rain gage is installed should be natural vegetation or gravel and not the paved one. The picture of a typical TE525 tipping bucket rain gage is shown in Figure 3-8 [11].

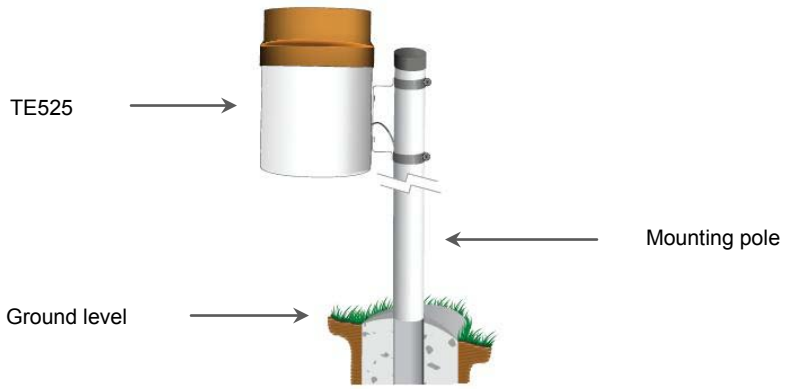


Figure 3-8 TE525 Tipping Bucket Rain Gage

TE525 has 3 wires: black, white and clear used for signal, signal return and shield respectively. CR10X and CR1000 both dataloggers have the capability of counting switch closures on some of their control ports. When a control port is used, the return from the rain gage switch should be connected to 5 V on the datalogger. The TE525 connections to CR10X and CR1000 dataloggers are shown below in Table 3-7 [11].

Table 3-7 TE525 wiring with CR10X and CR1000.

i) Wiring for Pulse channel input

DESCRIPTION	COLOR	CR10X	CR1000
Signal	Black	Pulse channel	Pulse channel
Signal return	White	G	⏚
Shield	Clear	G	⏚

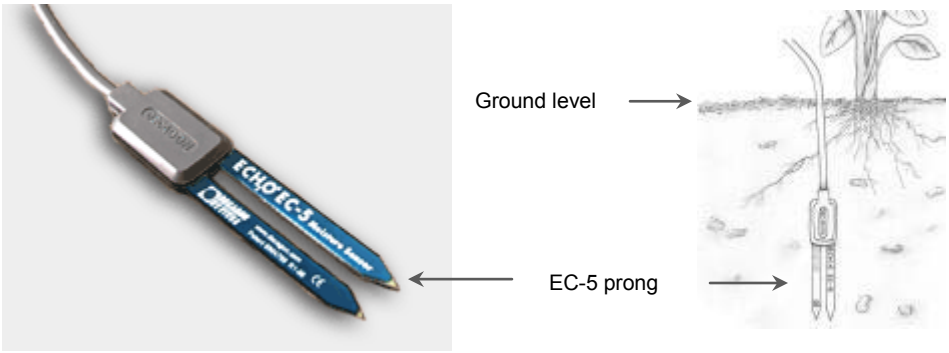
ii) Wiring for Control port input

DESCRIPTION	COLOR	CR10X	CR1000
Signal	Black	Control port	Control port
Signal return	White	5 V	5 V
Shield	Clear	G	⏚

f) Soil Moisture Sensor

EC-5 soil moisture sensor, manufactured by Decagon, is used for measuring the soil moisture. The sensor obtains volumetric water content by measuring the dielectric constant of the media through the utilization of capacitance/frequency domain technology. The operating temperature range of the sensor is -40º to +60ºC. The pointed prong design and higher measurement frequency allows the EC-5 to measure volumetric water content (VWC) from 0 to 100%, and allows accurate measurement of almost all soil types and much wider range of salinities. That means because EC-5 runs at higher measurement frequency, it is much less sensitive to variation in texture and electrical conductivity of soil The two pointed prongs design make it easy to install

anywhere even in hard or compact soil. However, it is better to insert the probe very carefully and gently while inserting into hard surface soil. Also the probe should be buried completely inside the ground surface as shown in Figure 3-9 (ii). The sensor is factory calibrated but it is recommended to perform soil specific calibration because the factory pre-calibration may not be applicable for all soil types. The nominal supply voltage is 3 V DC but can intake any voltage value from 2.5 to 3.6 V. A typical current consumption is about 10 mA [12].



i) EC-5 Soil Moisture Sensor ii) Inserting EC-5 probe inside ground

Figure 3-9 EC-5 Soil Moisture Sensor

The picture of a typical EC-5 is shown in the above Figure 3-9. EC-5 has 3 wires: red, white and clear used for analog out, excitation signal and shield respectively. The sensor output is fed to the single ended (SE hereafter) channel of the datalogger. The EC-5 probe connections to CR10X and CR1000 dataloggers are shown below in Table 3-9 [12].

Table 3-8 EC-5 wiring with CR10X and CR1000.

DESCRIPTION	COLOR	CR10X	CR1000
Analog out	Red	SE1	SE1
Excitation channel	White	E1	VX1
Shield	Clear	G	⏚

EC-5 Calibration

Even though the EC-5 probes come with pre-calibrated for most soil types, it is highly recommended that customers do perform re-calibration for specific soil types. Since the calibration equation varies with the soil types, appropriate calibration equation for specific soil type should be used. Following are the calibration equations for three different soil types (mineral soil, potting soil, and rockwool) for the probes excited at 2500 mV [12].

$$VWC = 11.9 \times 10^{-4} \times mV - 0.401 \quad \text{..... Mineral soils}$$

$$VWC = 10.3 \times 10^{-4} \times mV - 0.334 \quad \text{..... Potting soils}$$

$$VWC = 2.63 \times 10^{-6} \times mV^2 + 5.07 \times 10^{-4} - 0.0394 \quad \text{..... Rockwool}$$

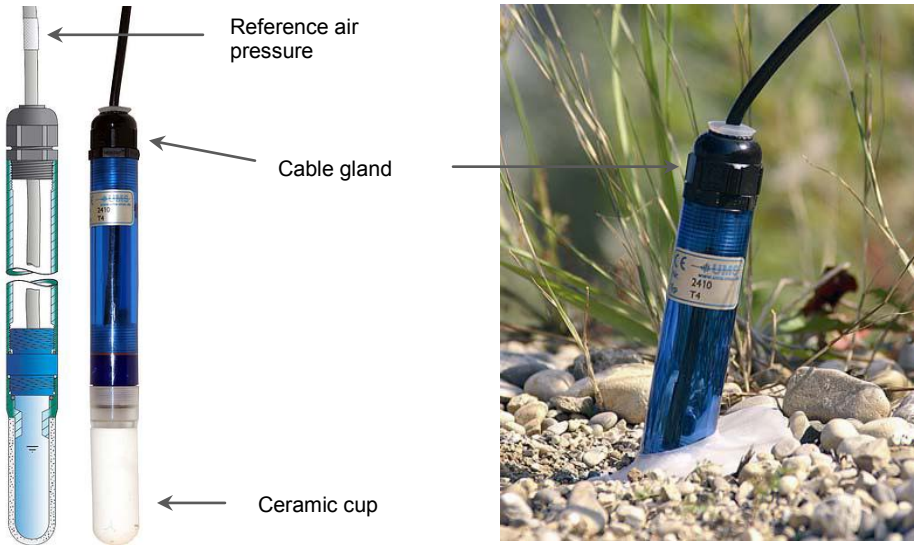
where,

VWC – volumetric water content of the soil

mV - output of the probe excited at 2500 mV [12].

g) Tensiometers

The T4 Tensiometer is used for measuring the soil water tension and soil water pressure. The sensor is factory calibrated with an offset of 0 kPa (when in horizontal position). Since the offset of the pressure transducer has a minimal drift over the years, it is recommended to check the sensors once a year and re-calibrate them every two years. The output signal of T4 tensiometer is directly dependent on the supply voltage and hence the supply voltage needs to be constant and stabilized. The typical supply voltage is 10.6 V DC but can intake any voltage value from 5 to 15 V. A typical current consumption is about 1.3 mA at 10.6 V. The measuring range of the T4 tensiometer is -85 kPa to 0 kPa of water tension. The picture of a typical T4 tensiometer is shown in Figure 3-10 [13].



i) T4 segments

ii) T4 deployed in field

Figure 3-10 T4 Tensiometer

T4 Tensiometer has 5 wires: brown, white, blue, black and thick black used for supply+, signal+, supply-, signal- and shield respectively. This means it uses DIFF channel of the datalogger. The TE525 connections to CR10X and CR1000 dataloggers are shown below in Table 3-9 [13].

Table 3-9 T4 wiring with CR10X and CR1000.

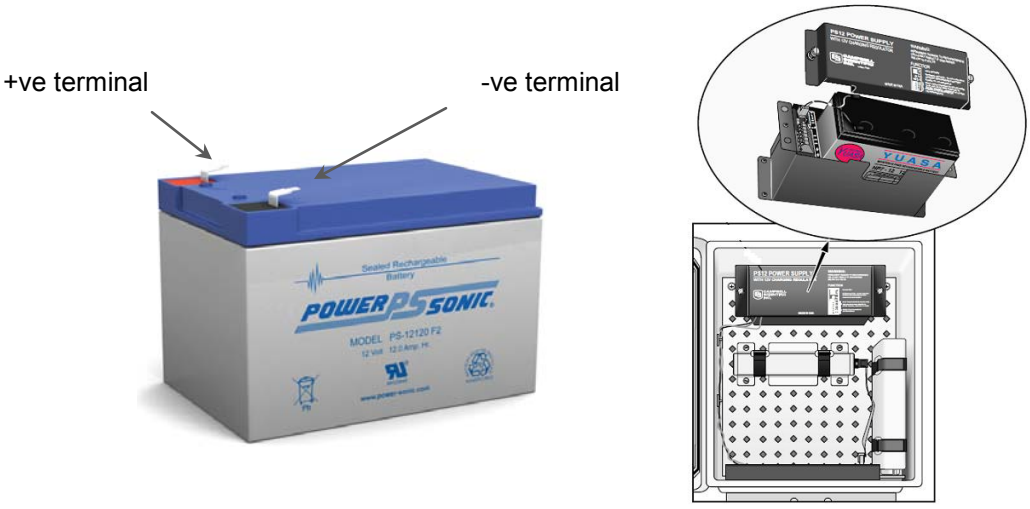
DESCRIPTION	COLOR	CR10X	CR1000
Supply+	Brown	5 V	5 V
Signal+	White	1H	1H
Supply-	Blue	AG	⏚
Signal-	Black	1L	1L
Shield	Thick black	G	G

3.1.3 Powering and Charging Devices

In order to perform any desired operation, an electrical power is required for all systems that consist of electrical and electronic devices. In addition to that, the power system is always expected to function well and its gravity is even higher in the system applications such as mobile services and etc. where even a few seconds of power failure is not tolerable. Depending upon the type of application, the components of a power system vary. The power system for this work is composed of battery backup, solar panel and charging regulator. Other elements such as AC power, power supply adapters etc are also discussed in this section.

a) Battery Backup

Battery backup is an important component of power system in weather monitoring application and it is indispensable when the weather station is installed in an area such as desert, forest etc. where there's no electricity. Battery is a power backup when there's no other power source to run the system. The batteries used in this project are from Power Sonic. There are various types of batteries available in the market. Some batteries are non-rechargeable, some are rechargeable, some are of low capacity, some are of high capacity etc. Selection of an appropriate battery type and capacity is also one of the important tasks in power system design perspective.



i) PS-12120

ii) Battery installation inside enclosure

Figure 3-11 12 V 12 Ahr Sealed Lead Acid Rechargeable Battery

A 12 V 7 Ahr and 12 V 12 Ahr sealed lead acid rechargeable batteries are chosen for the two stations in Greenbelt Corridor Weather Station. A 12 V 7 Ahr battery of same kind is chosen for DP_WS. A picture of a typical 12 V 12 A hr

sealed lead acid rechargeable battery (PS-12120) is shown in above Figure 3-11. It should be always connected to charging source through a charging regulator. In this work, battery is connected to solar panel through a charging regulator in every weather station. So in the day time when there's sunlight, it is charged by the solar panel and it supplies power to the system during whole night. But of course it should be charged enough in the daytime in order to supply power for whole night.

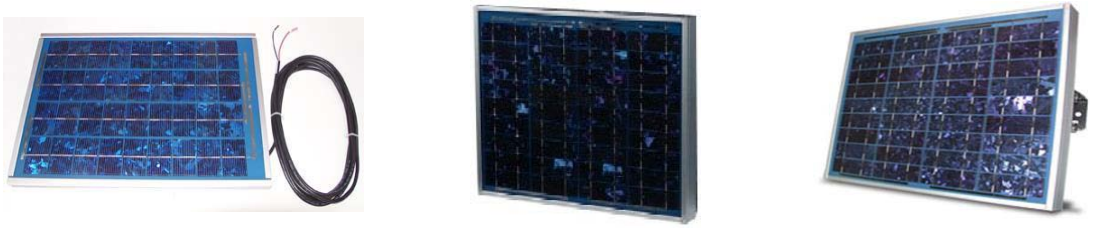
The battery should be fully charged before deploying in the field. Due to self-discharge characteristics of this type of battery, it is required to charge them after 6-9 months of storage, otherwise permanent loss of capacity might occur as a result of sulfation [14]. Some technical specifications of the battery (PS-12120) are given below in Table 3-10 [14].

Table 3-10 Technical specifications of PS-12120.

DESCRIPTION	SPECIFICATIONS
Name	PS-12120
Nominal Voltage	12 V
Nominal Capacity	12 Ahr
Max.Discharge current (≤ 7 min.)	36 Amp.
Max. short duration Discharge current (≤ 10 sec.)	120 Amp.
Approximate weight	3.86 kg
Operating temperature range	-20ºC to +50ºC

b) Solar Panel

Solar panel is one of the charging sources for rechargeable batteries. It is an essential charging source for those systems which are set up in an area where source of electricity is not available. Solar panel is a photovoltaic power source that converts solar energy into electrical energy. In other words, it converts the sunlight into direct current. Solar panel operates in both direct and diffuse light (cloudy days), but not at night. MSX10 and SX-20 U solar panels are used in GBC Weather Station and SP20 solar panel is used in DP Weather Station. Figure 3-12 below shows the pictures of different kinds of the solar panels used in this project.



i) MSX10 ii) SX-20 U iii) SP-20

Figure 3-12 Solar Panels

Among the three solar panels shown above in Figure 3-12, the MSX10 delivers a peak power of 10 W whereas the remaining two SX-20 U and SP-20 solar panels deliver a peak power of 20 W [15-17]. Like battery, selection of a solar panel is also an important task. Solar panel should be chosen such that it can charge the battery enough even within a short interval of sunlight especially during winter, rainy days and foggy days etc. Solar panels connect directly to

charging regulator whose 12 V output goes to datalogger input power supply terminal. In order to get maximum amount of sunlight, solar panel should be mounted facing south if located in the northern hemisphere or facing north if in the southern hemisphere. Also the tilt angle should be adjusted correctly which makes a lot difference in the output. Other technical specifications of these solar panels are given below in Table 3-11 [15-17].

Table 3-11 Technical specifications of solar panels.

DESCRIPTION	SPECIFICATIONS		
	MSX10	SX-20 U	SP-20
Output power (peak)	10 W	20 W	20 W
Output Voltage (peak) (voltage from solar panel before regulator)	17.5 V	16.8 V	17.1 V
Output current (peak)	0.57 Amp.	1.19 Amp.	1.17 Amp.
Guaranteed minimum peak power	9 W	18 W	18 W
Approximate weight	1.5 kg	3 kg	2.95 kg

c) Charging Regulator

A charging regulator must be used to connect rechargeable batteries with a charging source. The charging regulator controls the current flowing to the battery and prevents the battery current from flowing to the charging source. Charging regulator intakes an unregulated power from solar panel or AC wall charger and charges the battery connected to it as well as supply power to the system simultaneously. It is an essential element for almost all the systems that

require a constant voltage input supply. The charging regulators CH12R and CH100 are used in GBC Weather Station and DP Weather Station respectively. Actually, CH12R comes with PS12LA power supply which includes 12 V 7 A hr battery and CH100 comes with PS100 which includes 12 V 7 Ahr battery. Figure 3-13 below shows the circuit diagram of CH12R/CH100 charging regulator [18].

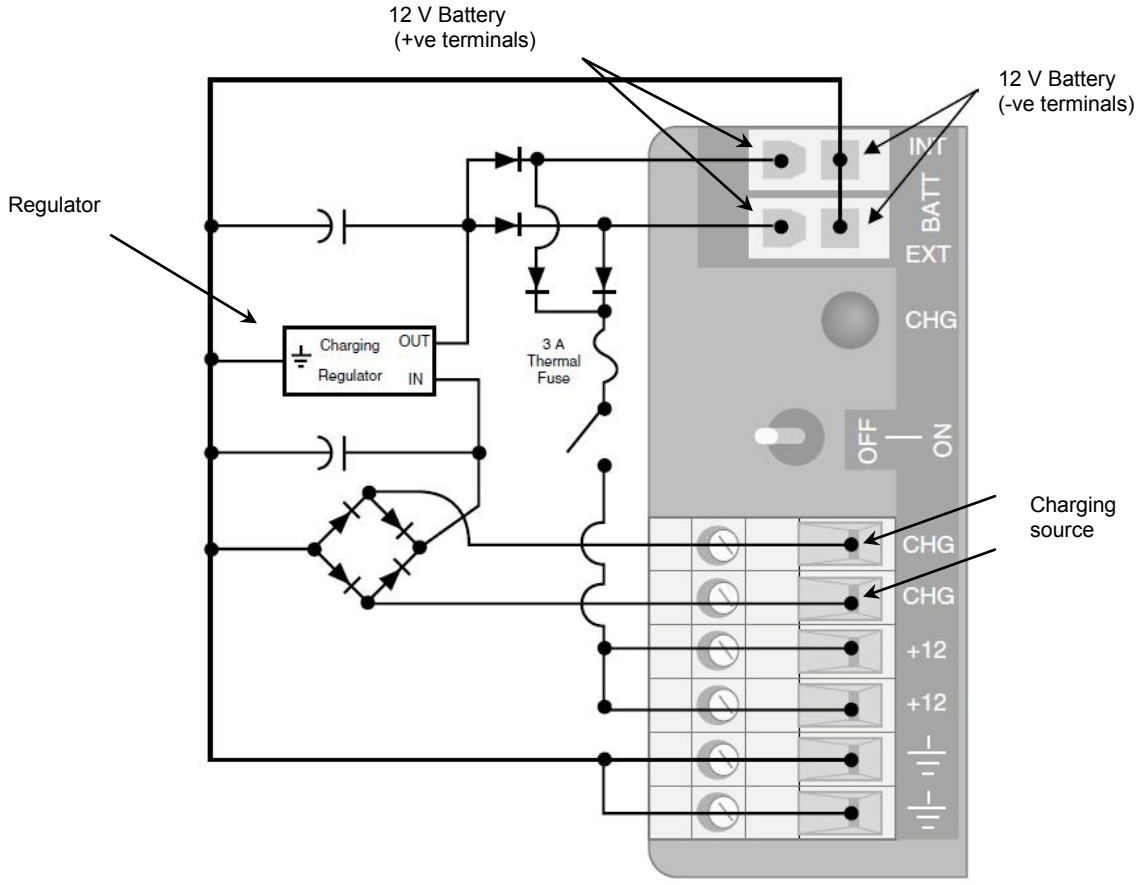


Figure 3-13 Charging Regulator Circuit Diagram

The above Figure 3-13 [18] clearly shows the circuit diagram of the charging regulator(s) being used. Because both the regulators CH12R and CH100 has the same circuitry, the figure above explains both. The Table 3-11 shows the technical specifications of the charging regulator [18].

Table 3-12 Technical specifications of charging regulator.

DESCRIPTION	SPECIFICATIONS	
	CH12R	CH100
Input voltage (CHG terminals)	15 - 28 V dc (18 V ac rms)	15 - 28 V dc (18 V ac rms)
Output voltage (+12 terminals)	12 V (unregulated from battery)	12 V (unregulated from battery)
Current limited	3 Amp.	3 Amp.
Temperature compensation range	-40 to +60ºC	-40 to +60ºC
Charging current limit	1.2 Amp.	1.2 Amp.

3.1.4 Optically Isolated RS-232 Interface (SC32B)

The SC32B optically isolated RS-232 interface is used to connect a CR10X datalogger's CS I/O port with a PC's RS-232 port. This interface is required for direct communication between a PC and a CR10X datalogger. CR1000 has both CS I/O port and RS-232 port, so any PC can directly connect to it via RS-232 port. It optically isolates the datalogger and RS-232 peripheral. Optical isolation separates the SC32B into a datalogger section and an RS-232

section. Signals entering from either side are electrically independent, protecting against ground loops, normal static discharge, and noise [19].

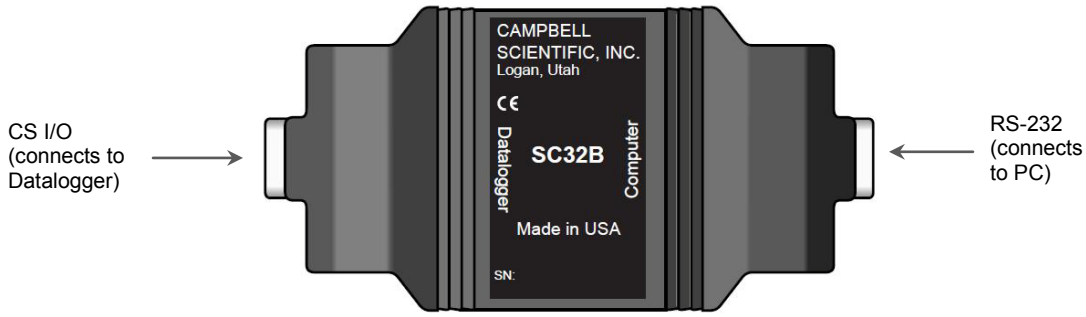


Figure 3-14 SC32B Optically Isolated RS-232 Interface

Figure 3 -24 sh ows a pi cture o f S C32B o ptically i solated i nterface. I t converts CR10X datalogger's logic levels to RS -232 l ogic levels allowing t he direct communication between the datalogger and the PC. The table 3-12 shown below gives some technical specifications of SC32B [19].

Table 3-13 Technical specifications of SC32B.

DESCRIPTION	SPECIFICATION
Power	5V, Powered by datalogger
Operating Temperature	-25 to +50ºC
Ports	9-pin female RS-232 configured as DCE 9 pin male CS I/O
Size	1.6"× 0.9"× 3.0"
Weight	45.4 g

3.2 Radio Components

Once the data collection is done in the field, they need to be carried to system server for analyzing and other necessary processing. So a wireless link between the weather station and internet source should be established. To accomplish this task, various components are used which are described in this section. Nanostation2, ethernet interface and switch are the radio components used for establishing the link and transferring data.

3.2.1 Nanostation2

Nanostation2 is a radio equipment manufactured by Ubiquity Networks that operates in 2.4 GHz frequency. The letter '2' is assigned just to indicate that the operating frequency of Nanostation2 is 2.4 GHz. Actually, there are also other products from the same manufacturer such as Nanostation3 and Nanostation5 operating in 3 GHz and 5 GHz frequencies respectively. Nanostation2 is a cheap and reliable product of the manufacturer with a high-gain 4 antenna system, advanced radio architecture and highly researched and developed firmware technology. Supporting the standards IEEE 802.11 b/g of Institute of Electrical and Electronics Engineers (IEEE hereafter), it is commonly used for establishing the wireless link between any two remotely located applications. In the present work application, it is used to link the DP_WS and the internet source in EESAT. It has a built-in directional antenna of 10 dBi gain. An external antenna can also be connected for longer transmission range. The transmit power of 26 dBm (max) allows it to cover the range of 15 km .The power

supply required for operation is 12 V 1 A with a potential of 4 W maximum power consumption. It can transmit up to 54 Mbps of data rate and 25 Mbps of throughput. Maximum receiver sensitivity is -97 dBm. The unit can be powered via the same Ethernet through which it is connected to other devices like PC, router or SBC etc. A picture of Nanostation2 is shown in different views in the below Figure 3-15 [20].

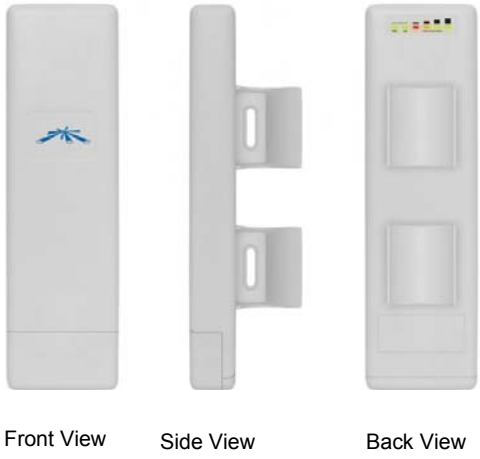


Figure 3-15 Nanostation2

Because the antenna inside the unit is directional, its radio signal propagates only in one direction from transmitter (Tx) to receiver (Rx) and this type of transmission is called LOS transmission. Nanostation2 uses commonly used vertical and horizontal polarization but besides that it also uses a new adaptive antenna polarity (AAP) technology which can improve the link quality. This new AAP technology allows Nanostation2 software switch antenna polarities statically or dynamically. It has a 3 dB horizontal beam width of 60º and vertical beam width of 30º [20].

Table 3-14 Technical specifications of Nanostation2.

DESCRIPTION	SPECIFICATION
Wireless	2.4 GHz
Operating frequency range	2.412 - 2.462 GHz
IEEE Standard	IEEE 802.11 b/g
Processor	Atheros 180 MHz MIPS
Memory	16 MB SDRAM, 4MB Flash
Networking interface	1×10/100 BASE-TX(Cat.5, RJ-45) Ethernet Interface
Antenna gain	10 dBi
Antenna polarity	Adaptive/Vertical/Horizontal (selectable)
3 dB Beamwidth	60º Azimuth, 30º Elevation
Data Rate	54 Mbps (max)
Throughput (TCP/IP)	25 Mbps (max)
Rx sensitivity	-97 dBm (max)
Tx power	26 dBm (max)
Transmission range	15 km
Extended transmission range	100 km (using external antenna)
Channel bandwidth	22 MHz
Channel spectrum width	5/10/20 MHz (selectable)
Power supply	12 V, 1 A
Power consumption	4 W
Operating temperature	-20º to +70ºC
Weight	0.4 kg

Table 3-14 shows some technical specifications of Nanostation2. Nanostation2 has 3 rate modes: quarter (5 MHz), half (10 MHz) and full (20 MHz). The Table 3-15 below shows data rate vs Rx sensitivity of 802.11b and 802.11g at given transmit power [21].

Table 3-15 Data rate vs Rx sensitivity.

FULL MODE (20 MHz)			
IEEE Standard	Tx Power	Data Rate	Rx Sensitivity
802.11b	26 dBm	1 Mbps	-97 dBm
		2 Mbps	-96 dBm
		5.5 Mbps	-95 dBm
		11 Mbps	-92 dBm
802.11g	26 dBm	6 Mbps	-94 dBm
		9 Mbps	-93 dBm
		12 Mbps	-91 dBm
		18 Mbps	-90 dBm
		24 Mbps	-86 dBm
	24 dBm	36 Mbps	-83 dBm
	23 dBm	48 Mbps	-77 dBm
	22 dBm	54 Mbps	-74 dBm

From the above table, it is seen that the Rx sensitivity is inversely proportional to data rate. So there should be a tradeoff between data rate and Rx sensitivity. Nanostation2 is operated by a firmware called Air OS. Air OS is an intuitive, versatile and highly developed Ubiquity firmware technology that is included with Nanostation2. Air OS is an operating system under which

Nanostation2 is built upon [21]. A very good thing about Air OS is its simplicity in using which makes it user friendly. And moreover it is powerful which enables high performance outdoor multi-point networking. The Nanostation2 can be accessed via any web browser. For the link to be established, one Nanostation2 should be set as access point and another a station mode. Following are the brief description of the web management pages of Nanostation2.

a) Main

Main page displays summary of link status information, current values of configuration settings and traffic statistics. Other utilities such as network administration and monitoring are accessible via this page. This page in station mode also displays the current receive signal strength (RSS). Also one can test the connection speed of the link using Tools feature. This tool can be used to estimate preliminary throughput between two network devices. Other status such as channel selected, local area network (LAN hereafter) media access control (MAC hereafter), wireless LAN (WLAN hereafter) MAC Tx rate, Rx rate, LAN IP address, WLAN IP address etc. are also displayed in this page. Also there's one feature named alignant enna which allows user to monitor RSS of the link continuously which is updated in every 1 sec and it is very useful especially while doing antenna alignment. In this page, using extra info, ARP and Bridge tables can be looked at. The Figure 3-16 below is a snapshot of the main page of Nanostation2 operating in station mode [21].

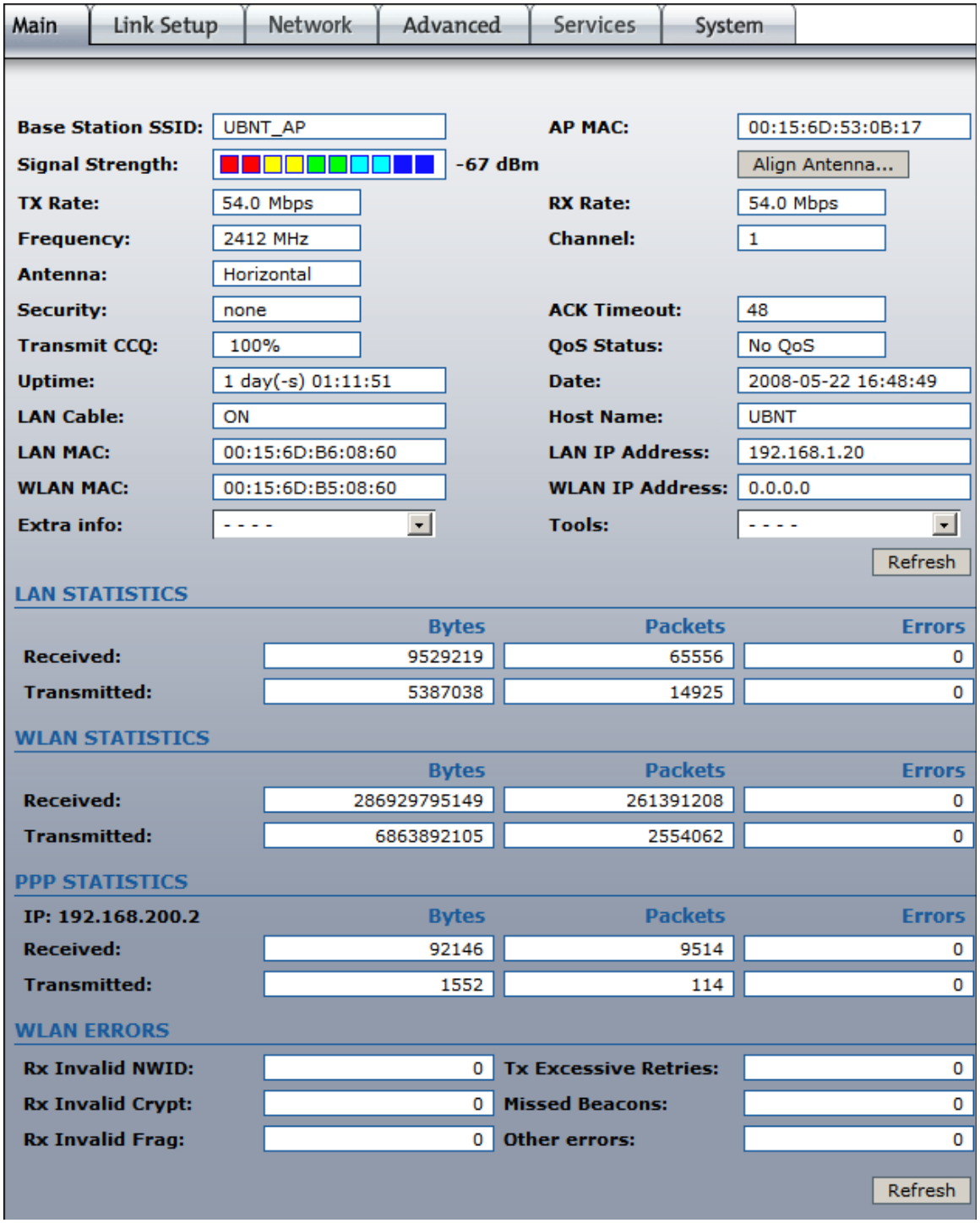


Figure 3-16 Main Page in Station Mode

b) Link Setup

This page allows user to set various wireless settings such as transmit output power, rate mode, IEEE 802.11 mode etc. Wireless mode feature allows choosing the appropriate mode such as station, station WDS, access point and access point WDS mode. It also allows the device in station mode to choose EESID. A 2.4 GHz band has only 11 channels used in United States, so one of them can be selected. This page allows user to set wireless security settings in three optional modes: wired equivalence privacy (WEP hereafter), Wi-Fi protected access (WPA) and WPA2. Station and station WDS modes are client modes which can connect to access point or access point WDS. The acronym WDS stands for wireless distribution system which allows equipments to bridge wireless traffic between devices which are operating in access point mode [21].

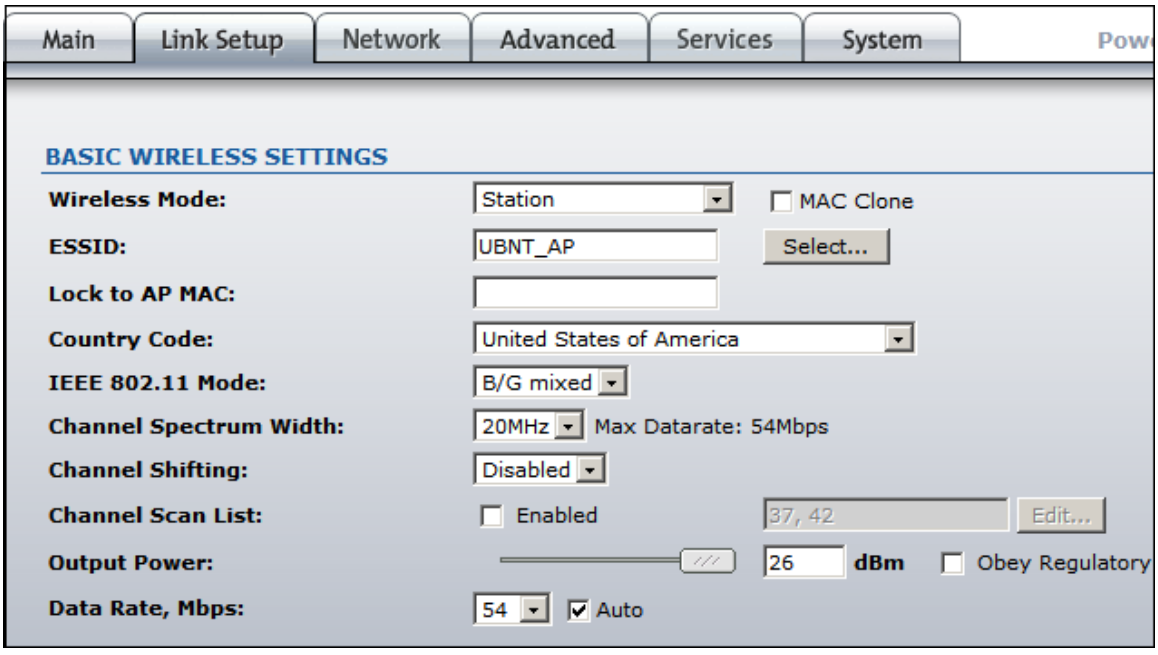


Figure 3-17 Link Setup Page in Station Mode

In IEEE 802.11 mode, there are 3 options: B only, B/G mixed and G only. If set to B only mode, then the device can connect to an 802.11b network only. Similarly, if set to G only mode, the device can connect to an 802.11g network only and if set to B/G mixed mode, then the device can connect to an 802.11b or 802.11g network. Another feature called rate mode has also three options for selecting spectral width of the radio channel which are quarter, half and full. This page also allows us to configure maximum output power of the device [21].

Figure 3-18 Link Setup Page in Access Point Mode

c) Network

This page allows user to configure network settings. At the very top of this page, operating network mode can be selected for the device either as bridge or router. Bridge operating mode is selected by default as it is widely used by the subscriber stations, while connecting to access point or using WDS. The device will act as a transparent bridge forwarding all the network management and data packets from one network interface to another without any intelligent routing. WLAN and LAN interfaces belong to the same network segment, so there will be no network segmentation while broadcast domain will be the same [20-21].

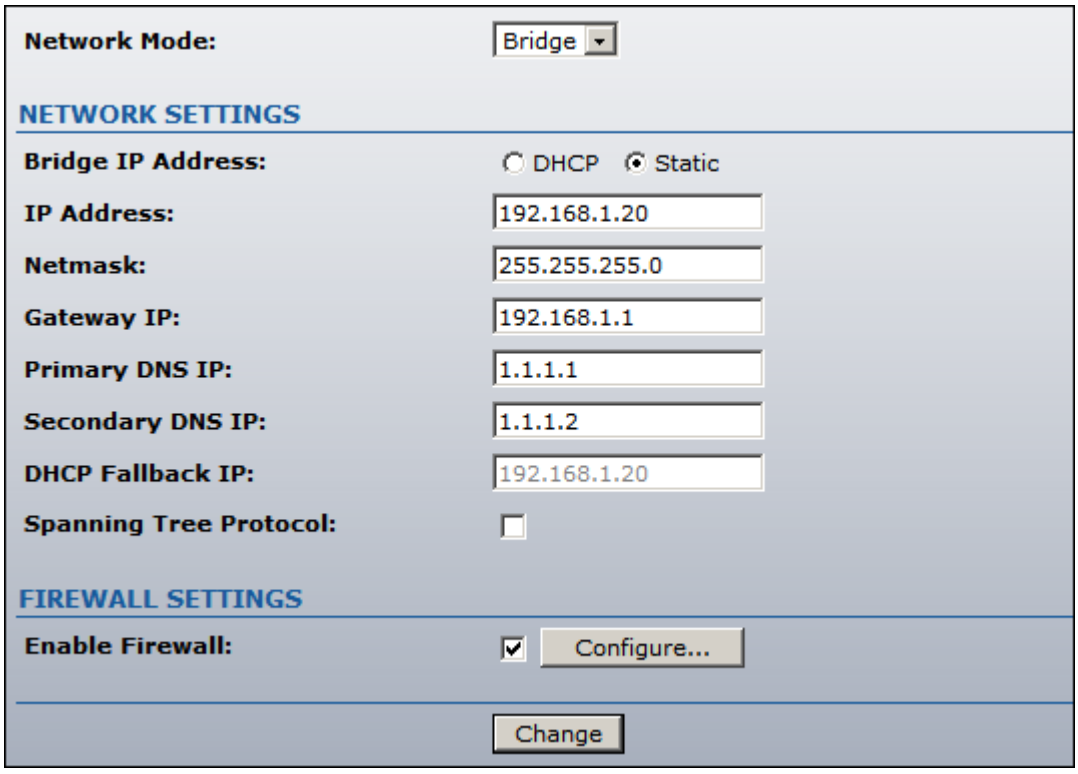


Figure 3-19 Network Page in Bridge Mode

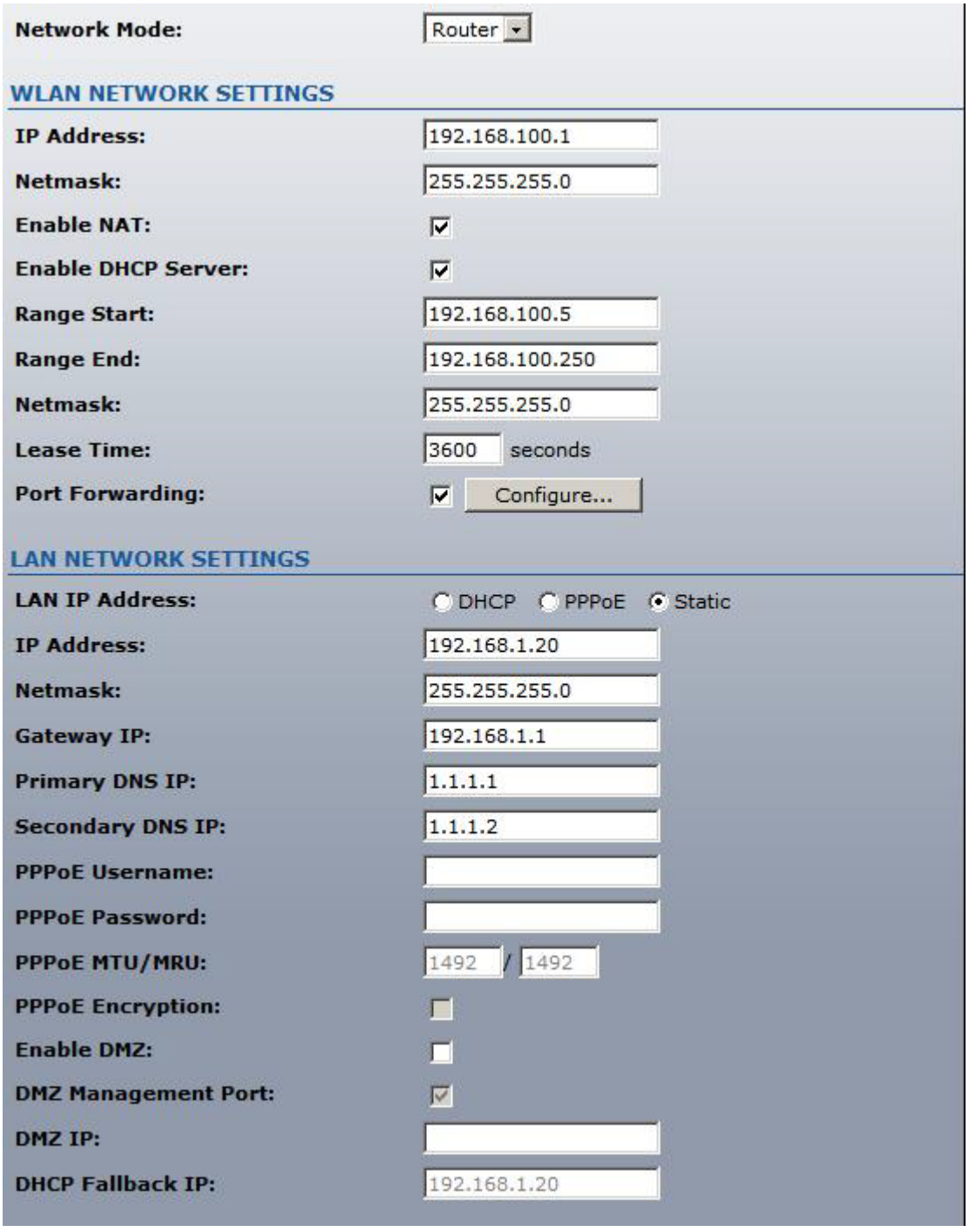


Figure 3-20 Network Page in Router Mode

Router operating mode can be configured to perform routing and enable network segmentation. In this mode, wireless clients will be on different IP subnet. Router mode will block broadcasts while it is not transparent. The Air OS powered device (Nanostation2 here) can act as Dynamic Host Configuration Protocol (DHCP) server and use network address translation feature which is widely used by access points. Figure 3-20 shows typical configuration settings of network page in router mode [21].

d) Advanced

This page allows user to manage and handle advanced routing and wireless settings. There are three options for selecting rate algorithm which are as follows: Optimistic, conservative and exponentially weighted moving average (EWMA). Rate algorithm has a very crucial impact on performance of outdoor links which selects data packet transmission algorithm depending upon the rate mode selected (in link setup page) and the data transmission throughput [21].

Optimistic algorithm always tends to achieve maximum throughput at the cost of sacrifice of noise immunity and robustness. It is more prone to individual packet failure. It starts with the highest possible rate and then decreases till the rate can be supported while periodically transmitting packets at higher rates and computing the transmission time. Conservative algorithm is less prone to individual packet failure. This algorithm looks carefully at number of successful and erroneous transmission/retransmission over a certain period of time and accordingly it steps down to a lower rate after continuous failure of packet

transmission and steps up to higher rate after a number of successful packet transmissions. It offers the best stability and robustness but at the cost of degraded throughput. EWMA algorithm is a hybrid of above two mentioned algorithms. So it is the compromise for most of the wireless networks. Below is the snapshot of advanced page operating in conservative rate algorithm mode [21].

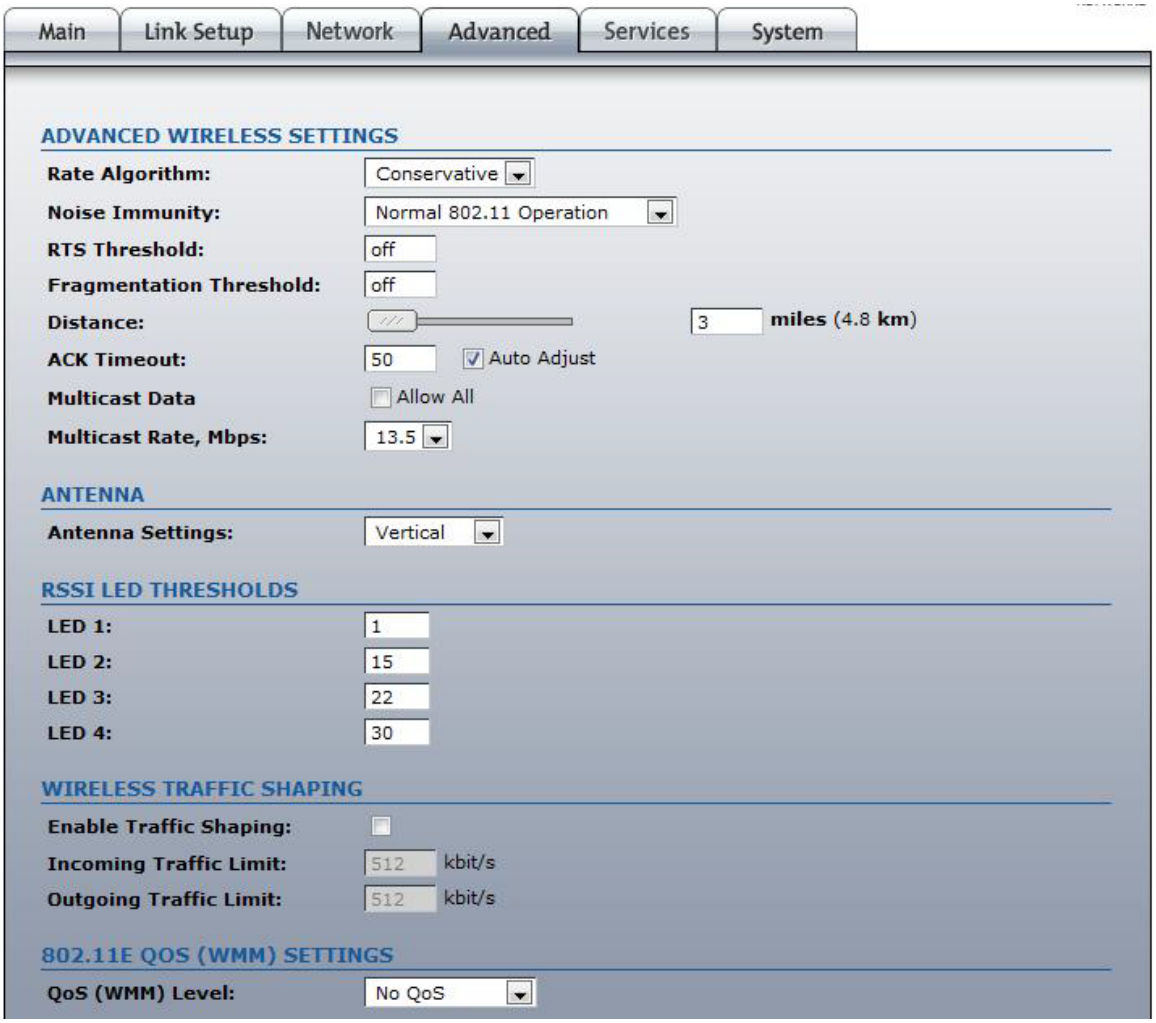


Figure 3-21 Advanced Page in Conservative Rate Algorithm Mode

This page has antenna settings allowing us to choose the antenna polarization. Three options are vertical, horizontal and adaptive polarizations. Vertical and horizontal polarization systems are quite common and hence widely used but the new adaptive polarization technique dynamically chooses the best polarity. It allows beam polarities to switch dynamically to get better reception for improved performance even in heavily noisy environments also. Besides these advanced page allows user to set and select different parameters such as noise immunity, request-to-send (RTS) threshold, multicast data, and multicast rate etc [21].

e) Services

This page covers the configuration of system management services Simple Network Management Protocol (SNMP hereafter) and ping watchdog. It has ping watchdog feature that includes several other features like enable ping watchdog, IP address to ping, ping interval, startup dlay and failure count to reboot. After enabling ping watchdog by checking on the checkbox, it continuously pings the target device whose IP address is defined in IP address to ping box. The ping works by sending Internet Control Message Protocol (ICMP) "echo request" to the destination host and listening for ICMP "echo response" replies. It has another tool known as SNMP agent for monitoring and managing other network devices. SNMP agent provides an interface for device monitoring using SNMP. It allows network administrators to monitor network performance, find and solve problems. Services page is shown in Figure 3-22 [21].

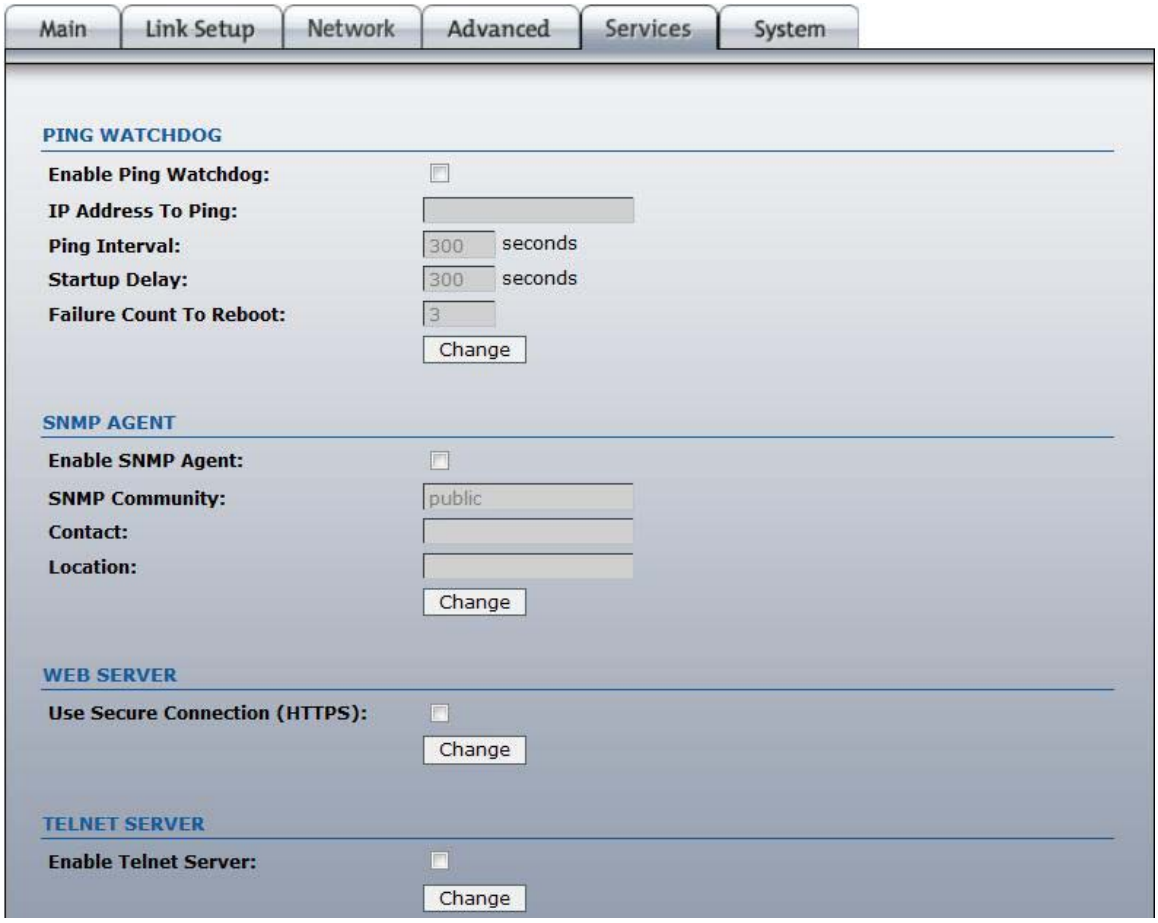


Figure 3-22 Services Page

Web s erver ca n be s et as secure Hypertext T ransfer P rotocol Secure (HTTPS) mode by ch ecking on t he b ox of use secure c onnection (HTTPS). default m ode is Hypertext T ransfer P rotocol (HTTP hereafter). Also i n t elnet server, enable telnet server box can be checked on to enable telnet access to the Air OS device [21].

f) System

This page contains various administrative options. This page allows administrator to customize various configuration and reboot the device. Administrator can upgrade a new firmware in firmware version tool. Also this page allows him to change host name, set and change the administrator's username and password.

In configuration management tool, there are two configurations: Backup configuration and upload configuration. One can click on download button of backup configuration tool to download the current system configuration file so that so that the system can be restored using the downloaded system configuration file when the system crashes or something bad happened. And also if you want to change the system configuration file, then browse button of upload configuration tool can be clicked to select a new system configuration file and upload button can be clicked to transfer that new configuration file. That new system configuration file will take effect after apply button is activated and the system is rebooted. It is highly recommended that you keep the backup of the system configuration file before uploading a new configuration file. And another important thing is use only configuration files backups of same device type for that the backup configurations file of Nanostation2 only works for Nanostation2 and doesn't work for any other device type such as Powerstation2 or Litestation2 or Nanostation5 etc. The snapshot of system page is given in Figure 3-23 [21].

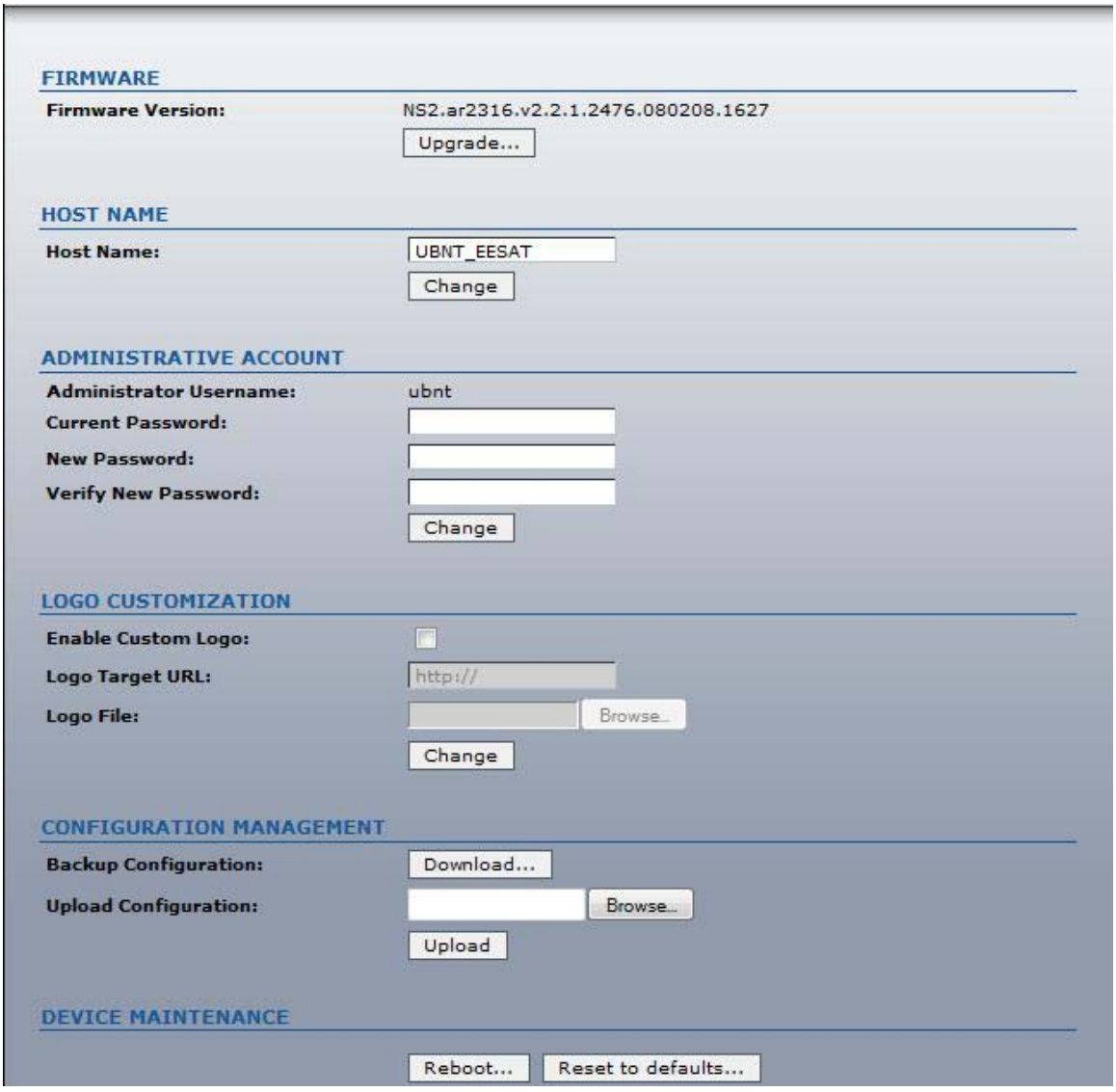


Figure 3-23 System Page

3.2.2 Ethernet Interface

Ethernet interface is used to connect those devices which don't normally have an ethernet port on it with a PC making it possible for communication between them. The ethernet interface that will be used in this project is NL120 from Campbell Scientific Inc that allows the CR1000 datalogger to communicate over a local network or a dedicated internet connection via TCP/IP [22]. Pictures of a typical NL120 (left) and its connection to 40-pin peripheral port of CR1000 datalogger (right) are shown in the Figure 3-26 below.

i) NL120 ii) NL120 connected to 40-pin peripheral of CR1000

Figure 3-24 NL120

Table 3-16 Technical specifications of NL120.

FEATURE	SPECIFICATION
Voltage	12 Vdc
Current drain	20 mA
Support software	Loggernet 3.2 or later, PC400 1.3 or later
Operating system	PakBus
Standard Temperature Range	-25ºC - +50ºC
Dimension	4.0" × 2.5" × 1.1"
Weight	2.35 oz

3.2.3 Network Switch

A switch or a network switch is a computer networking device that connects multiple computers and peripherals together within one local area network (LAN). Network switches operate at data link layer (layer 2) of Open System Interconnection (OSI) reference model. The main function of a switch is to forward the data packets to the correct destination ports after processing them. A network switch enables sharing of multiple computers, peripherals such as printers, wireless routers etc. within a LAN. It acts as an intermediate station which interconnects the communication links and sub networks to enable transmission of data between the end stations [23].

Figure 3-25 Network Switch

In this work, a network switch will be used to interconnect the Nanostation2 and ethernet interface NL120 which are used in DP_WS. The Figure 3-25 [24] shown above is of a typical 8-port network switch.

CHAPTER 4

DATA COLLECTION PROCEDURE

Data collection is the process of collecting environmental data of a particular area by deploying a weather station connected with various environmental sensors. The descriptions of sensors and other devices used in the system are already discussed in Section 3.1 of Chapter 3. In this chapter, there is a detailed description about how those sensors and devices are wired with the weather station, how they are controlled by software to collect the data from the field and how the data are transmitted to the CRI system server using two different wireless technologies. A brief description of datalogger support software and programming to run the datalogger are also given in this chapter.

As already discussed earlier, the two stations GBC_WS and DP_WS are being deal with. Block diagrams of overview of environmental monitoring systems of both the stations are discussed in Figure 2-2 and Figure 2-4.

4.1 Greenbelt Weather Station (GBC_WS)

In this section, focusing on data collection procedure, mainly three sub-topics will be discussed: Functional overview of GBC_WS, datalogger support software (PC208W) and Edlog programming editor used to run the datalogger for data collection.

4.1.1 Functional Overview: Greenbelt Weather Station (GBC_WS)

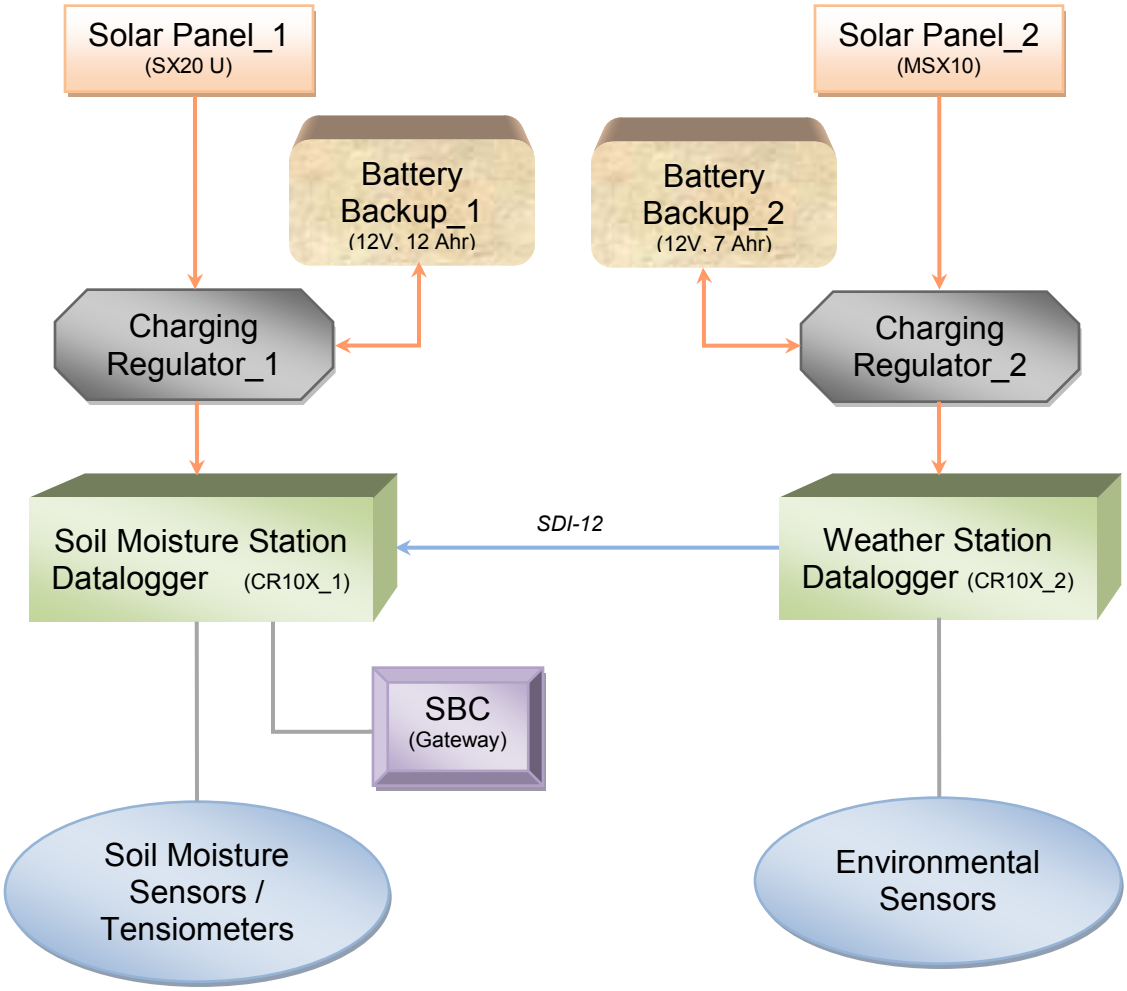


Figure 4-1 Functional Overview: Greenbelt Weather Station (GBC_WS)

Above Figure 4-1 is the functional block diagram of GBC_WS. There are two stations in Greenbelt: one is a soil moisture station measuring soil moisture and soil water pressure and another is a weather station measuring various kinds

of environmental parameters. A CR10X datalogger is used as a measurement and control module in both stations.

Both the stations are powered by a sealed lead acid rechargeable battery. soil moisture station is powered by a 12 V, 12 Ahr battery whereas weather station is powered by a 12 V, 7 Ahr battery. Because electricity is not available in GBC_WS, a solar panel is used as a charging source. SX20 U and MSX10 are the solar panels used in soil moisture and weather stations respectively. A charging regulator (CH12R) is connected to both solar panel and battery as well. Different kinds of environmental sensors are connected with weather station datalogger and soil moisture sensors and tensiometers are connected with soil moisture station datalogger. There is also an SBC connected with the soil moisture datalogger.

In the day time, solar panel supplies power to the system and charges the battery as well. Battery gives power to the system during night and also that time whenever the solar panel is not powering the system due to insufficient sunlight. In the above Figure 4-1, you can see different colors are assigned for the lines connecting the blocks. Faint red line indicates the flow of power, faint blue line is for indicating the flow of collected data and gray line indicates the line connecting the blocks of sensors and other devices connected to the datalogger. To indicate that the flow of current is bidirectional, both ended arrow headed faint red lines are used.

Every 15 minutes, data are collected by dataloggers via sensors connected to both the stations. After that, the collected data of Weather datalogger are transferred to soil moisture datalogger via SDI-12 sensor. All the data collected from both the dataloggers are stored in soil moisture datalogger data storage module. Then the data are transmitted to CRI system server via SBC and GPRS modem.

4.1.2 PC208W: Datalogger Support Software for CR10X

PC208W is a datalogger support software for CR10X datalogger that facilitates programming, communication and reliable exchange of data between a PC and a CR10X datalogger. When a CR10X datalogger is connected with a PC208W installed PC, then after clicking the software icon, the main window will be opened which is shown in Figure 4-2 given below. There are 8 different buttons in PC208W toolbar having their different unique functions which are discussed below [25].

Figure 4-2 PC208W Main Window

- *Setup:* This toolbar allows you to configure devices including dataloggers, COM ports, modems and other communication devices. In this toolbar, you

can also configure other settings such as data collection and scheduled communications settings [25].

- *Connect:* After successfully setting up your datalogger, you can now access the datalogger just by clicking on Connect button. Here in this Connect window, you can do many tasks such as setting data logger's clock, sending programs from PC to datalogger, collecting data from storage module, viewing and making graph measurements etc [25].

- *Status:* Status toolbar is used for displaying information for all the dataloggers on the device map at one glance. Also it is used for checking the status of data collection including scheduled calls, errors, retries, and how much data was collected [25].

- *Program:* Program toolbar is used for creating and editing the data logger program with EDLOG editing toolbar. It also allows the users to insert comments in between the program codes [25].

- *Report:* Report allows us to sort and combine data based on time and conditions, splits large data files into smaller files that can be analyzed more easily. One can also perform data processing using arithmetic operators, math functions and time-series functions and can create the output files compatible in excel formats [25].

- *View:* This toolbar allows us to view or graph the data files which are originally saved in comma separated, binary, or printable American Standard for Information Interchange (ASCII) format [25].
- *Help:* Help toolbar is for PC208W datalogger support software help.

File Types

To run the CR10X datalogger for data collection from the field, a program written in Edlog editor is sent to datalogger in Connect toolbar. The only compatible program file type that can be sent to the CR10X datalogger is in .DLD (Download) format. Actually a .DLD file is automatically created by compiling an Edlog program file which is in .CSI format. CSI files are the Edlog program files that the user edits. When an Edlog program is saved, .CSI extension is automatically added to the program's name. Also .FSL (Final storage label) and .PTI (Program trace information) files are automatically created during program compilation. The .FSL files list the final storage labels and are used by SPLIT to help select output values. The .PTI files show the execution times for each instruction, block, and table as well as the number of final storage locations used per day. The library files having .LBR extension allows us to insert a section of a program into any Edlog program [25].

The collected data output file type which is downloaded from datalogger to the PC is .DAT. The .INI (Initialization) files provide the PC208W program with specific information such that the devices or program defaults don't have to be reconfigured every time when PC208W and dataloggers are connected. The

datalogger's .INI files are created/updated each time when it disconnects the communication with PC208W and .INI files of PC208W are created/updated each time it is closed. The .DND (Datalogger network configuration) files are used to keep the setup information. Parameter files are in .PAR extension which are created by SPLIT and defines which data files are read, what operations are performed on the data set and where the final results will be saved. .PAR files can be saved and used time to time [25].

Data Collection

After successful connection of a CR10X datalogger with a PC having PC208W installed, data can be transferred to the PC from datalogger storage module simply by clicking on Collect or Collect All button in manual data collection of Connect toolbar. Collect button allows us to transfer data of a desired time frame whereas with the Collect All button all the data can be transferred to PC from the datalogger storage module. Normally, datalogger is configured with a PC208W to collect the data from the field automatically just by toggling on Schedule On in schedule tab of Setup toolbar, but if it is desired, then it can be configured for one time data collection also. Also a PC208W can be set to enable the PC collect data automatically. For this, the schedule for the device (CR10X here) can be copied to other devices by selecting "Apply to Other Stations" in schedule tab. And if PC208W is put in the windows startup group, it automatically loads when the PC is turned on and starts to collect the data automatically [25].

4.1.3 EDLOG: Programming Editor for CR10X

An EDLOG is a tool for creating, editing and documenting program especially for a CR10X datalogger. However, it is also available in modern datalogger support software such as LoggerNet 3.4.1. In an Edlog editor, a complete datalogger program for almost all kinds of measurement can be written and saved. When an Edlog program is saved, a .CSI extension is automatically added after the program's name. It is the only file which users can edit and save again and again.

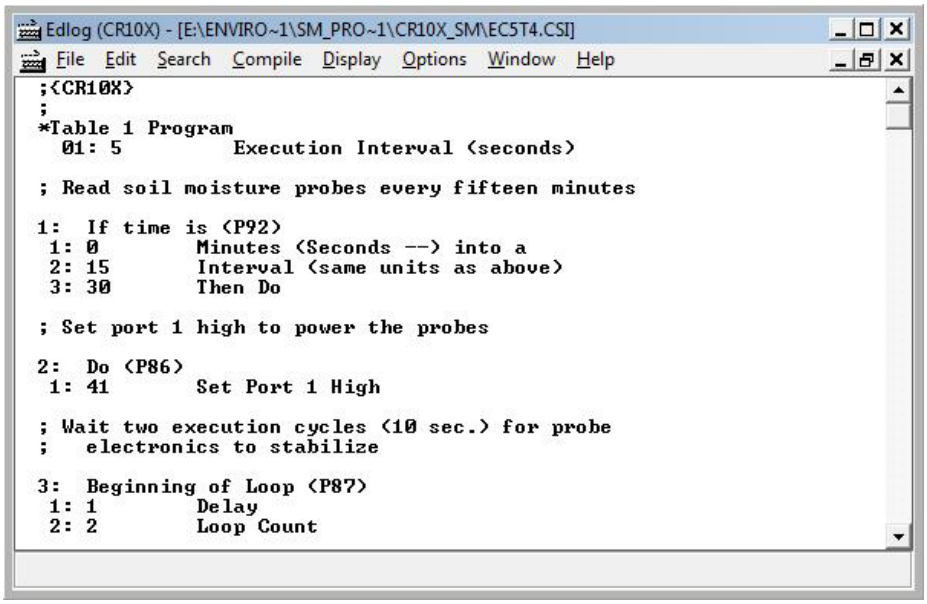

Edlog (CR10X) - [E:\ENVIRO~1\SM_PRO~1\CR10X_SM\EC5T4.CSI]
File Edit Search Compile Display Options Window Help
;<CR10X>
;
*Table 1 Program
01: 5 Execution Interval (seconds)
; Read soil moisture probes every fifteen minutes
1: If time is (P92)
1: 0 Minutes (Seconds --) into a
2: 15 Interval (same units as above)
3: 30 Then Do
; Set port 1 high to power the probes
2: Do (P86)
1: 41 Set Port 1 High
; Wait two execution cycles (10 sec.) for probe
; electronics to stabilize
3: Beginning of Loop (P87)
1: 1 Delay
2: 2 Loop Count

Figure 4-3 .CSI Input Program File

Figure 4-3 shows a snapshot of a typical .CSI program file written in Edlog editor. When this program is compiled in Edlog compiler, then a .DLD file is created automatically which is sent to datalogger later. A snapshot of a .DLD file

formed after compilation of the above .CSI program is shown in the Figure 4-4 below. Final storage label (.FSL) files are also automatically created when an Edlog program is compiled.

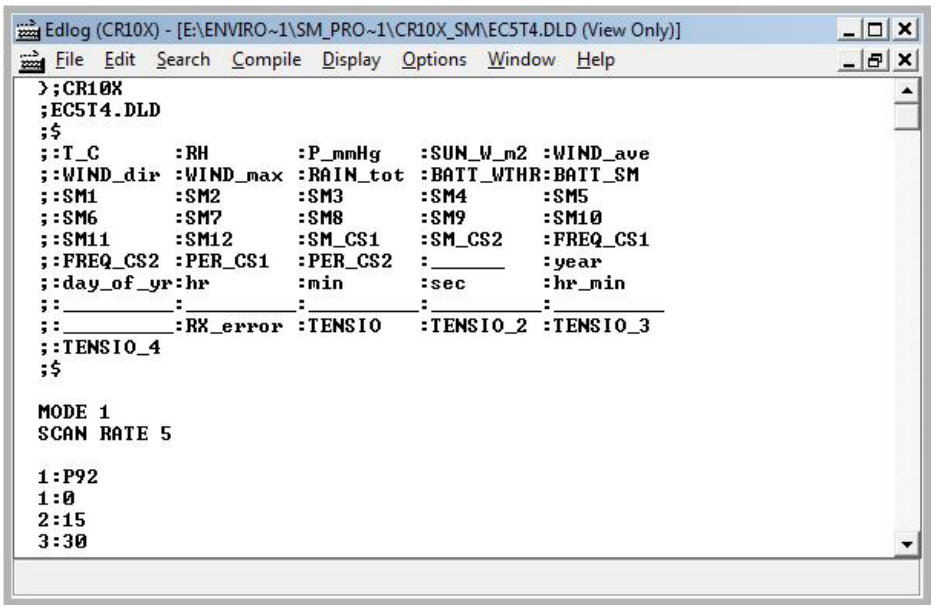


Figure 4-4 Edlog .DLD Program File

Figure 4-5 is a snapshot of a typical .FSL file created after program compilation. The .FSL file lists the final storage labels for each data element.

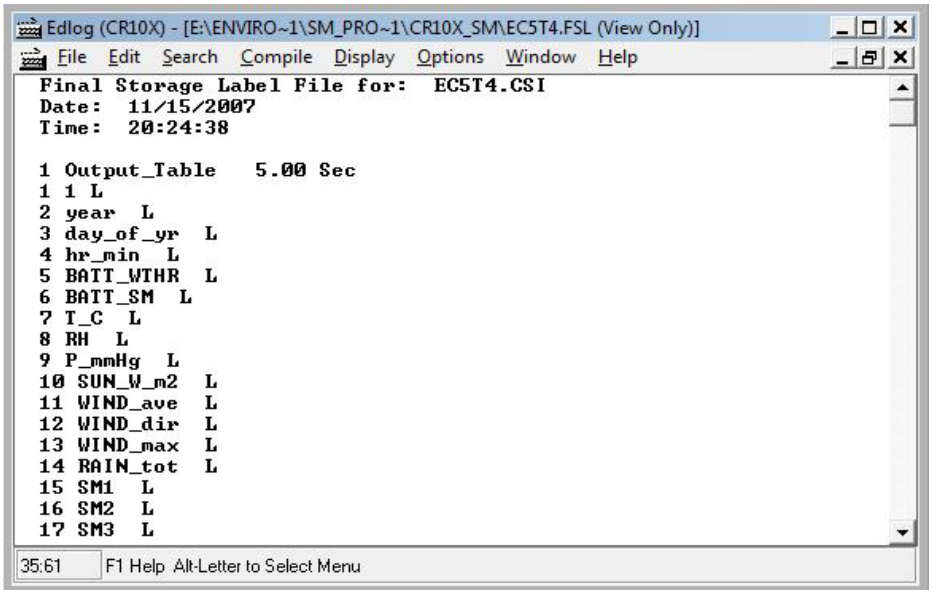


Figure 4-5 Edlog .FSL Program File

PC208W supports three file formats for the collected data which are ASCII-coma separated, ASCII-printable and binary. ASCII-coma separated is the best selection for most applications where data values are separated by commas with no leading zeros and with each array on a new line. This is the easiest format for importing into other software and can be viewed directly [25].

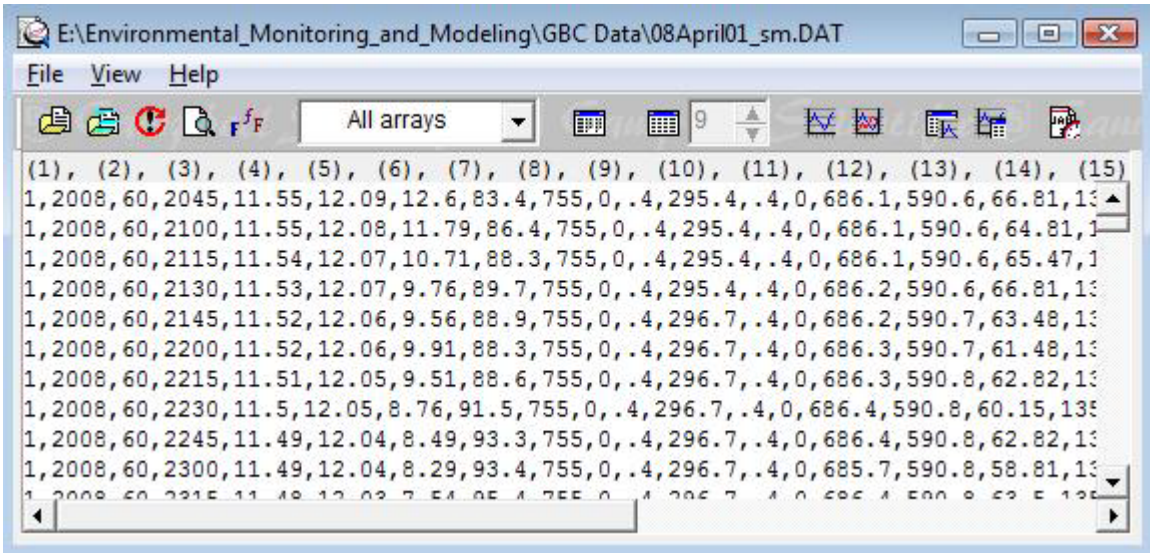


Figure 4-6 ASCII, Comma Separated Input File

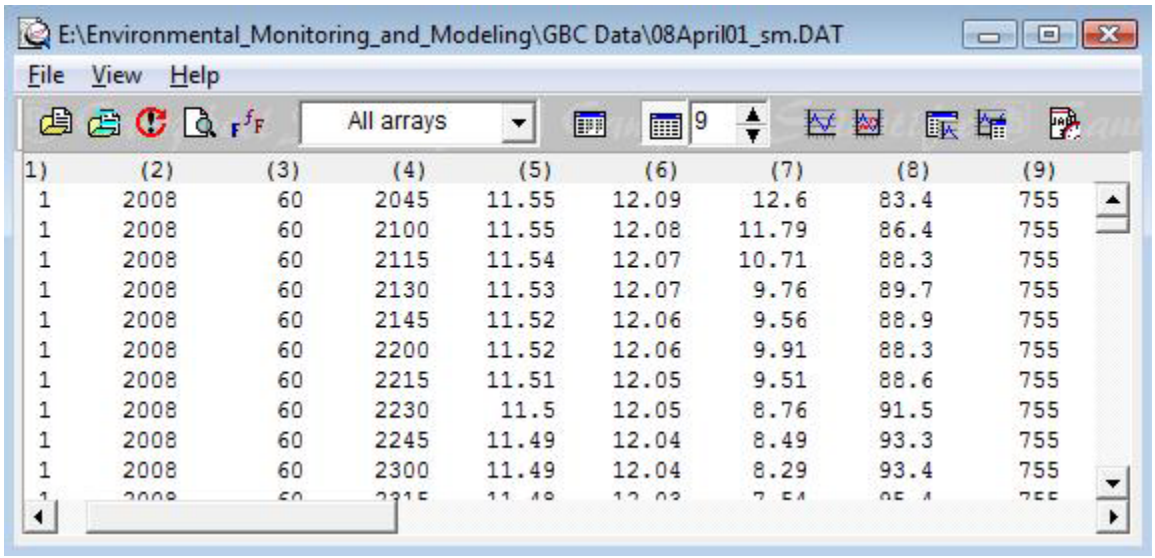
In ASCII-printable format, data are aligned in columns and preceded by a 2-digit ID indicating the array position. This format is easiest to read manually and hence it is user friendly for viewing and analyzing the collected data. But it is difficult to import into spreadsheets and other applications. SPLIT can be used for converting to other formats. This data format is not reliable for data arrays of about 100 or more [25].

01+0001	02+2008	03+0060	04+2045	05+11.55	06+12.09	07+12.6	08+83.4
01+0001	02+2008	03+0060	04+2100	05+11.55	06+12.08	07+11.79	08+86.4
01+0001	02+2008	03+0060	04+2115	05+11.54	06+12.07	07+10.71	08+88.3
01+0001	02+2008	03+0060	04+2130	05+11.53	06+12.07	07+9.76	08+89.7
01+0001	02+2008	03+0060	04+2145	05+11.52	06+12.06	07+9.56	08+88.9
01+0001	02+2008	03+0060	04+2200	05+11.52	06+12.06	07+9.91	08+88.3
01+0001	02+2008	03+0060	04+2215	05+11.51	06+12.05	07+9.51	08+88.6
01+0001	02+2008	03+0060	04+2230	05+11.50	06+12.05	07+8.76	08+91.5

Figure 4-7 ASCII-Printable Input File

Binary format is the most compact and hence the size of the file is much smaller than for the above mentioned ASCII based files. Because the binary format is not in readable form, it should be converted by SPLIT to make it in readable format [25].

SPLIT can convert these files in different other formats but they must be in compatible form for conversion. The input files for SPLIT must be formatted in comma separated ASCII, final storage (binary) format, field formatted ASCII (SPLIT default output format), printable ASCII, or raw A/D data [25]. The comma separated ASCII and printable ASCII input files are shown in above figures Figure 4-6 and Figure 4-7 respectively. The input file type of the field formatted ASCII is shown below in Figure 4-8.



(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
1	2008	60	2045	11.55	12.09	12.6	83.4	755
1	2008	60	2100	11.55	12.08	11.79	86.4	755
1	2008	60	2115	11.54	12.07	10.71	88.3	755
1	2008	60	2130	11.53	12.07	9.76	89.7	755
1	2008	60	2145	11.52	12.06	9.56	88.9	755
1	2008	60	2200	11.52	12.06	9.91	88.3	755
1	2008	60	2215	11.51	12.05	9.51	88.6	755
1	2008	60	2230	11.5	12.05	8.76	91.5	755
1	2008	60	2245	11.49	12.04	8.49	93.3	755
1	2008	60	2300	11.49	12.04	8.29	93.4	755

Figure 4-8 Field Formatted ASCII Input File

4.2 Discovery Park Weather and Soil Station (DP_WS)

This section also discusses three sub-topics: Functional overview of DP_WS, datalogger support software (LoggerNet 3.4.1) and CRBasic programming editor used to run the datalogger for data collection. This section also discusses an alternative program creating tool for CR1000 known as transformer utility. The program created using the transformer utility can directly be sent to the datalogger. In addition to this, this section also includes some future work such as ethernet interface installation and its configuration which will enable to connection between the datalogger and the Nanostation2.

4.2.1 Functional Overview of DP_WS

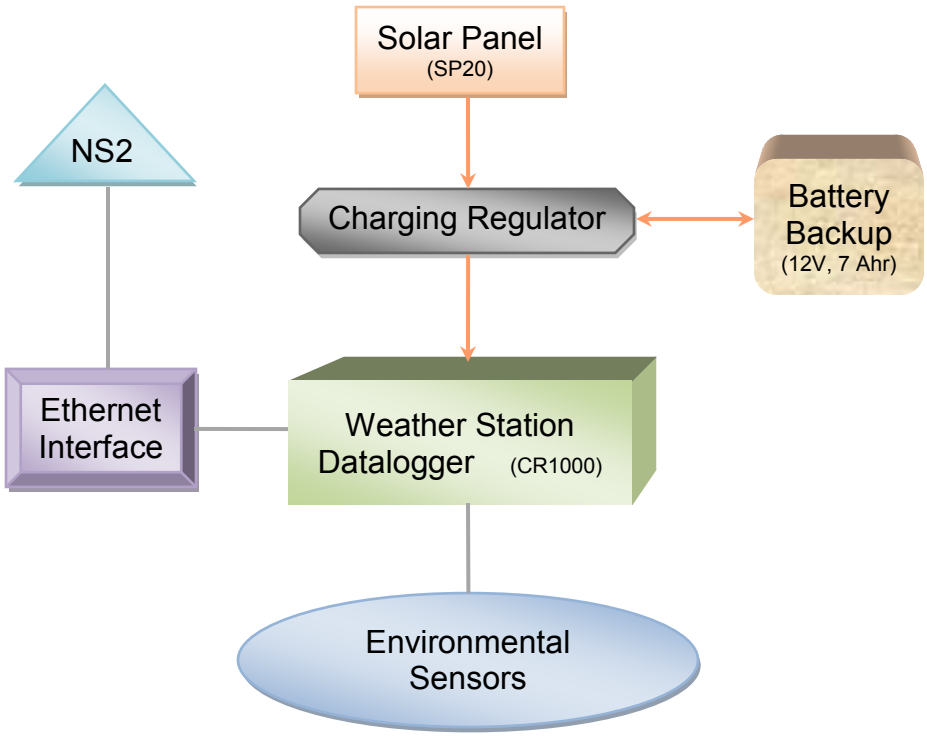


Figure 4-9 Functional Overview of DP_WS

Above Figure 4-9 is the functional block diagram of DP_WS. There is one station in DP_WS measuring various kinds of environmental parameters. A CR1000 datalogger is used as a measurement and control module.

As in GBC_WS, the DP_WS is also powered by a 12 V, 7 Ahr sealed lead acid rechargeable battery. A SP20 solar panel is used as a charging source. A charging regulator (CH100) is connected to both solar panel and battery as well. Different kinds of environmental sensors and soil moisture sensors are connected with weather station datalogger. There is also an ethernet interface connected with the datalogger and the Nanostation2.

In the day time, solar panel supplies power to the system and charges the battery as well. Battery gives power to the system during night and also that time whenever the solar panel is not powering the system due to insufficient sunlight. The color indices in above Figure 4-9 are same as in Figure 4-1

At every 15 minutes, data are collected by dataloggers via sensors connected in the station. All the data collected from the datalogger are stored in the datalogger data storage module. Then the data are transmitted to CRI system server via ethernet interface and Nanostation2.

4.2.2 LoggerNet 3.4.1: Datalogger Support Software for CR1000

LoggerNet 3.4.1 is a full featured datalogger support software datalogger that enables users to setup, configure and retrieve data from a network of Campbell Scientific dataloggers and share this data over ethernet communication network. Loggernet software supports communication and data collection for

Edlog dataloggers such as CR10X and CRBasic dataloggers such as CR1000 and etc. Loggernet is especially designed for applications that require telecommunication or scheduled data retrieval used in large datalogger networks. When a CR1000 datalogger is connected with a Loggernet installed PC, then after clicking the software icon, the main window will be opened which is shown in Figure 4-10 given below. There are 12 different buttons in loggernet toolbar having their different unique functions which are discussed below [26].

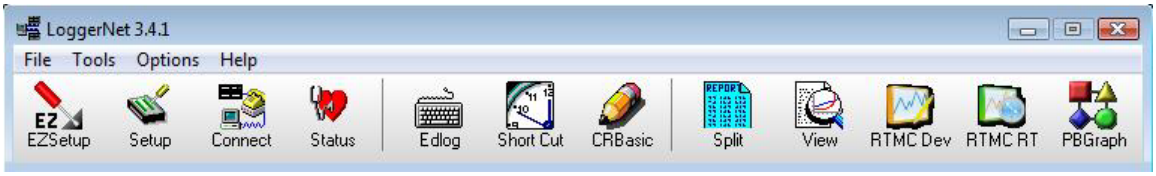


Figure 4-10 PC208W Main Window

- *EZSetup:* This is the first wizard used to set the CR1000 datalogger to make it able to communicate with PC. This is the primary wizard which allows you to setup and configure devices including dataloggers, COM ports, modems and other communication devices. In this toolbar, you can also send program files to the datalogger, set datalogger clock, test communication link between PC and CR1000 datalogger, configured data collection and scheduled communications settings [26].

- *Setup:* Setup screen is divided into two parts: Device map in the left and Set up tabs in the right side of the screen. If you want to add a COM port, just click on "Add Root" and select ComPort or alternatively right click within the white space of the Device map and choose ComPort from the list of options

for root devices. Devices can be added just by clicking Add button in this screen. When you highlight any device on the network shown on the left side of the Setup window, configuration tab appears on the right side with the relevant settings [26].

- *Connect:* After successfully setting up your datalogger, you can now access the datalogger just by clicking on Connect button. The connect screen provides a real time connection to a datalogger in the datalogger network. Here in this Connect window, you can do many tasks such as setting data logger's clock, sending programs from PC to datalogger, viewing and collecting data from storage module, viewing and making graph measurements etc [26].

- *Status:* Status toolbar is used for displaying information for all the dataloggers on the device map at one glance. The leftmost column of the status monitor displays the network map showing the devices in the network. It provides a control over the Loggernet data collection process, configure the display appearance, or bring up other applications such as Log tool or PakBus graph [26].

- *Edlog:* Edlog toolbar is used for creating, editing and documenting programs for Campbell Scientifics' mixed array dataloggers such as CR10X and etc. Edlog supports all operating systems for these dataloggers, including table-data (TD) and PakBus (PB) versions. Edlog also allows comments to be

inserted. An Edlog compiled program file, which is in .DLD format, can be sent to datalogger [26].

- *Short Cut:* The Shortcut is an application for generating programs for all of the Campbell Scientific dataloggers. It is also referred to as SCWIN. It also generates a wiring diagram for connecting the sensors the datalogger. It is especially designed for the beginning datalogger programmers to create a datalogger program easily and quickly in four easy steps. These four steps are: Select the datalogger, choose how often and which sensors you wish to measure, select intervals or trigger conditions on which to store data and what processing to perform on the raw measurements for final storage. Short Cut is not suitable for complex applications that require more control over measurement programs and programs that require supporting all of the functionality in Campbell Scientific dataloggers [26].

- *CRBasic:* CRBasic is also a full featured datalogger program editor that has more control over measurements. This tool is intended especially for experienced datalogger programmers who need more flexibility and control over the datalogger operation which can't be achieved by using Short Cut. More detail of CRBasic programming is described in Section 4.2.3.

- *Split:* Split is a tool used to post process the collected data from dataloggers. Split allows us to sort and combine data based on time and conditions, splits large data files into more easily analyzed smaller files. One can also process

data using arithmetic operators, math functions and time-series functions and can create the output files compatible in excel formats [26].

- *View:* View is a simple file viewer that provides a way to look at the collected data files. These files are saved in various formats including files from mixed-array and table-based dataloggers. View can open the following file types: .DLD, .CSI, .PTI, .FSL, .LOG, .CR2, .CR5, .CR1, .CR3, .CR8, .CR9. This toolbar allows us to view or graph the data files which are originally saved in comma separated, tabular (field formatted), or hexadecimal format [26].

- *RTMC dev:* The Real time monitor and control (RTMC hereafter) software provides the ability to create and run graphical screens to display real time data as Loggernet collects it from the dataloggers. RTMC can combine data from multiple dataloggers on a single display. RTMC has two operating modes: Development (RTMC Dev) and Run-Time (RTMC RT). Development mode allows users to create and edit a real time graphic display screen to display the collected form dataloggers. Then the screen is built and saved as a file. Different types of graphical components can be combined to create an attractive real-time display [26].

- *RTMC RT:* The real-time graphic screen (the screen which was created in RTMC Dev mode) can be displayed using RTMC-Run time. So, once a project file has been created, the display screen can be run without starting

the RTMC Dev mode window. In RTMC Run-time mode, also the image displayed in the RTMC display screen can be printed [26].

- *PB graph:* PakBus (PB) Graph provides a visual representation of the devices depicting the connections in a Loggernet PakBus datalogger network and lets you edit PakBus device settings. PakBus Graph window is divided into three parts: the list of PakBus devices, a graphical depiction of the PakBus network, and the log messaged for PakBus communication. PakBus Graph can be opened from the Status Monitor, the Troubleshooter, or from the LoggerNet toolbar's Tool menu [26].

Transformer Utility

Transformer utility is a stand-alone utility designed for converting an existing datalogger program created in Edlog into a CRBasic program. It is installed as one of the utilities with LoggerNet that can be launched from Windows start menu. Transformer utility is offered in Loggernet especially for those users of CR10X or CR23X dataloggers who are switching to CRBasic dataloggers such as CR800, CR1000 and CR3000 [26]. For example, in this present work, when switching from CR10X to CR1000 datalogger, Transformer utility successfully transformed an Edlog program file (.CSI/.DLD) into a CRBasic file (.CR1).

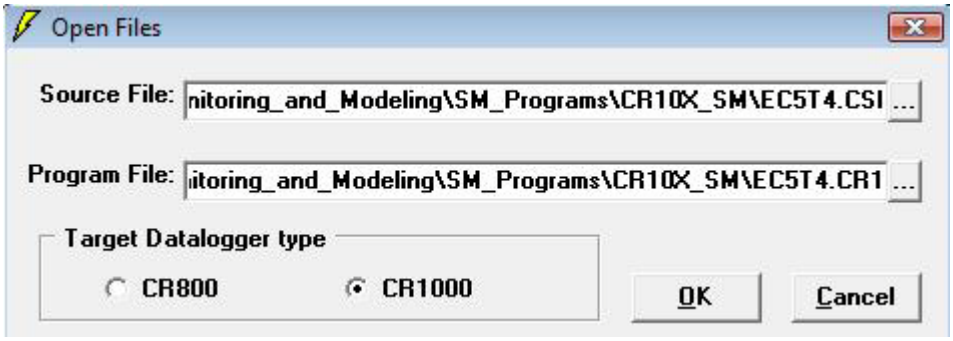


Figure 4-11 Transformer Utility: .CSI to .CR1 Input Files

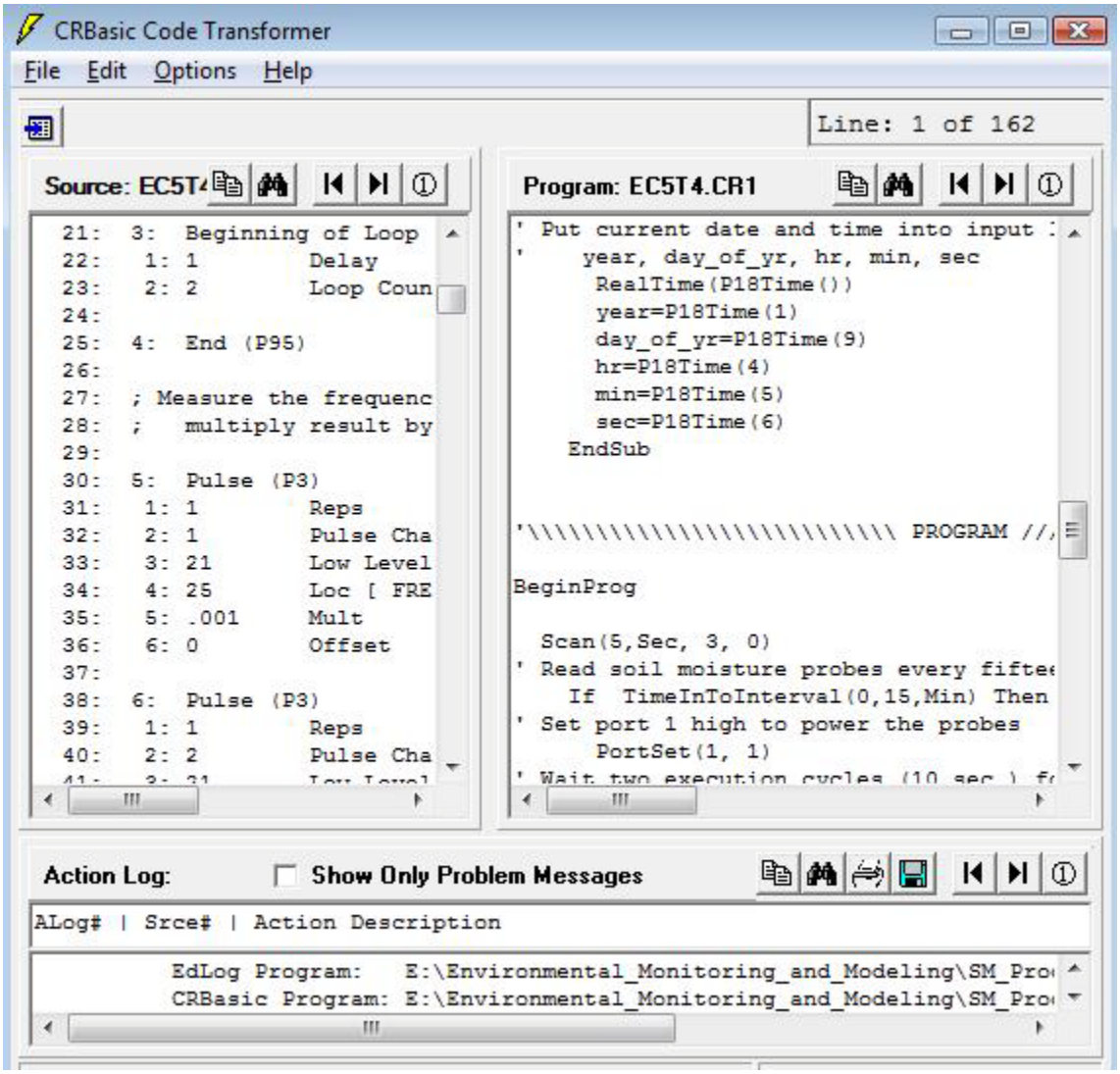


Figure 4-12 Transformer Utility: .CSI to .CR1 Output Files

The Figure 4-11 above shows a window of a Transformer Utility. The source file is the Edlog program file which is either .CSI or .DLD that is to be converted and the program file is the new .CR1 file that will be created after conversion. The Figure 4-12 above shows a window of a Transformer Utility showing the CRBasic file is created in the right window and Edlog (source) file is opened up in the left window. In most of the cases, such converted .CR1 files can be directly sent to CR1000 datalogger. But sometimes, the converted program code may need some fixing such as defining some unknown variable for CRBasic though it is known for Edlog.

Transformer utility is not installed in Loggernet window, instead it is installed in a separate window which can be opened from Windows start menu following the track: *Start/Programs/LoggerNet/Utilities/Transfomer* [26]. So, you can't see this wizard in Loggernet main window shown in Figure 4-10.

File Types

For CR1000 datalogger to operate for data collection, a CR1000 compatible program file is needed to be sent to the datalogger which can be accomplished either in Connect toolbar or in EZSetup wizard. The only compatible program file that can be sent to the CR1000 datalogger is in .CR1 format. A .CR1 file can be created by 3 different ways: writing program in CRBasic editor, generating program using Short Cut or converting from Edlog program code to CRBasic program.code using Transformer Utility [26].

Talking about the file formats that are supported by LoggerNet 3.4.1, it can support almost all the file types that are supported by PC208W such as .CSI, .DLD, .PTI, .FSL, .DAT etc. and it supports other file types such as .CR2, .CR5, .CR1, .CR3, .CR8, .CR9 etc [26].

Data Collection

After successful connection of a CR1000 datalogger with a PC having LoggerNet 3.4.1 installed, data can be transferred to the PC from datalogger storage module simply by clicking on Collect Now button in Connect toolbar in main window of LoggerNet 3.4.1. Normally, datalogger is configured with a LoggerNet to collect the data from the field automatically just by checking on Scheduled Collection Enabled box either in EZSetup wizard or in Schedule tab of Setup wizard. Also a Loggernnet can be set to enable the PC collect data automatically. For this, the schedule for the device (CR1000 here) can be copied to other devices by selecting Apply to Other Stations in Schedule tab of Setup wizard. And if LoggerNet 3.4.1 is put in the Windows startup group, it automatically loads when the PC is turned on and starts to collect the data automatically [26].

4.2.3 CRBasic: Programming Editor for CR10X

A CRBasic is a tool for creating, editing and documenting program that has more control over measurements and which is designed especially for dataloggers such as CR1000 and etc. This tool is intended especially for

experienced datalogger programmers who need more flexibility and control over the datalogger operation which can't be achieved by using Short Cut. In a CRBasic editor, a complete datalogger program can be written and saved. When a CRBasic program is saved, a .CR1 extension is automatically added after the program's name. It is the file which users can edit again and again.

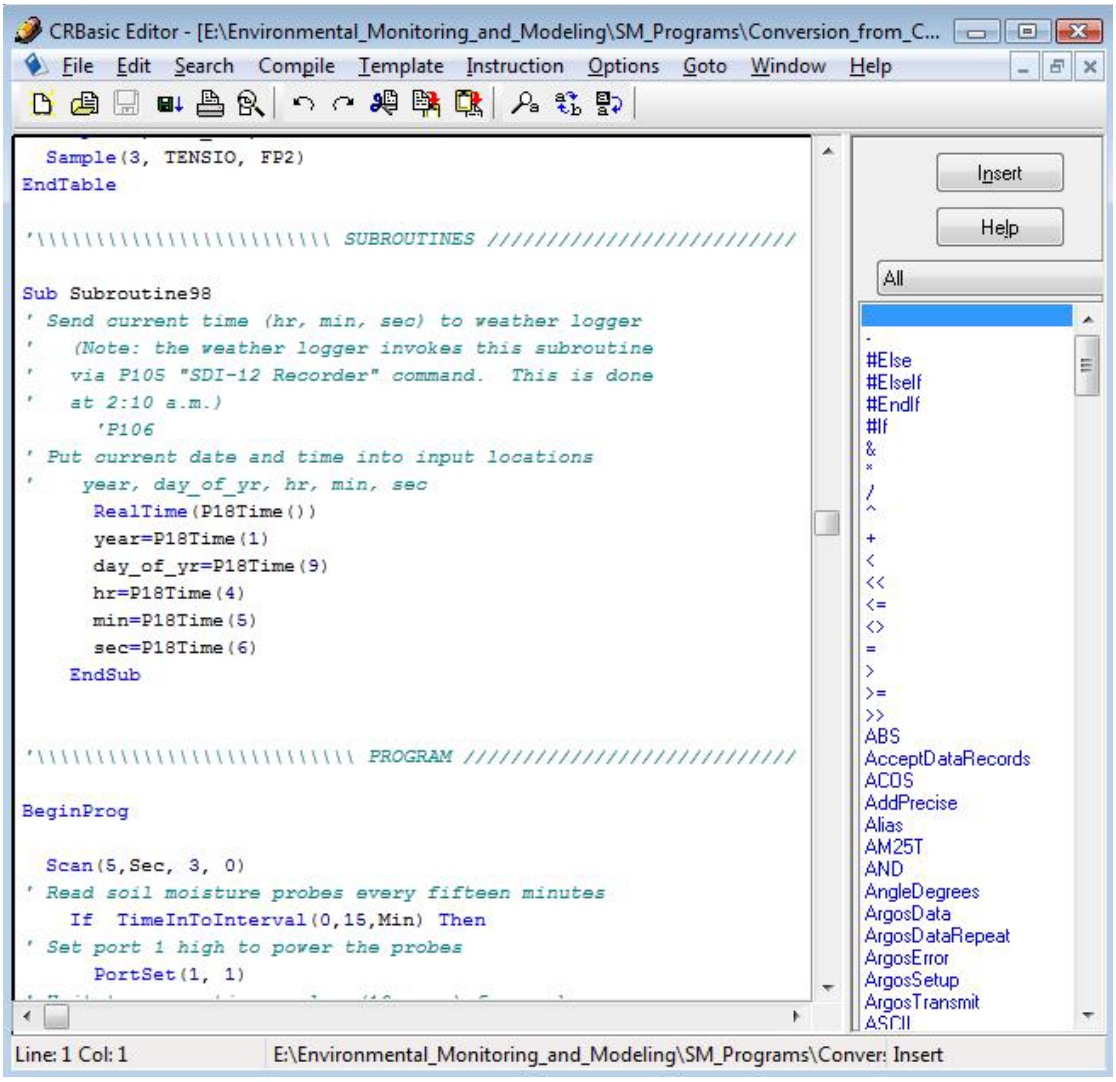


Figure 4-13 CRBasic .CR1 Input Program File

Figure 4-13 shows a snapshot of a typical .CR1 program file written in CRBasic editor. The programming language is similar to structured Beginner's All-purpose Symbolic Instruction Code (BASIC) programming language in syntax, program flow and logic. The variables, data tables, and subroutines should be declared before they can be used and this can be accomplished by outing all the variables declarations and out put table definitions at the beginning. Comments can be easily inserted in this programming language either by putting apostrophe (') mark at the beginning of the line containing comments or after program code [26].

After compilation of CRBasic program and having sent to CR1000 datalogger, data can be viewed in three different views using LoggerNet 3.4.1. These are Normal-Comma separated, Expand Tabs-field formatted and Hex-hexadecimal format. The first two Normal and Expand Tabs views are exactly similar to previously discussed Comma separated and Field formatted file types of Figure 4-6 and Figure 4-8 of Section 4.1.3 except than that they don't bear headlines at the top whereas Loggernet facilitates data view of .CR1 file with headlines which makes easier to read the collected data [26]. The Figure 4-14 below shows a collected data from DP_WS in Normal view.

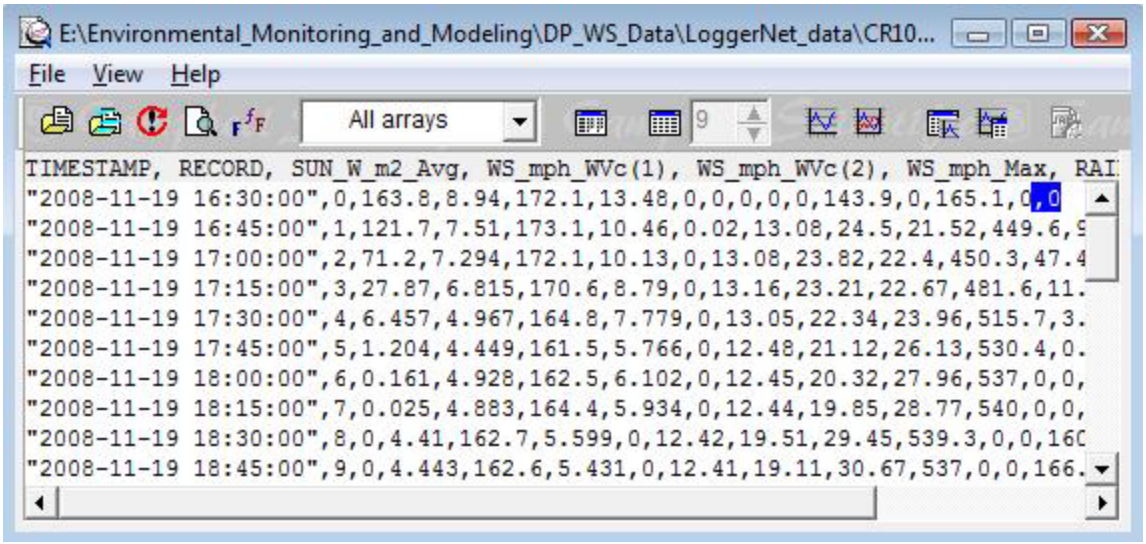


Figure 4-14 Normal View-Comma Separated

In Expand Tabs view also, data are aligned in columns with a tab separation. This format is easy to read manually. The Figure 4-15 below shows a collected data from DP_WS in Expand Tabs view.

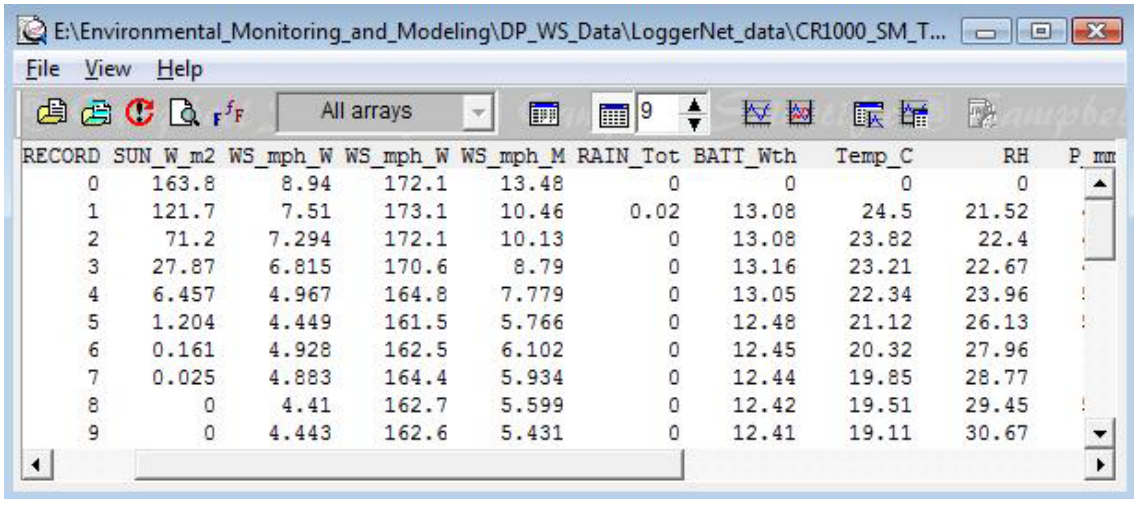


Figure 4-15 Expand Tabs View-Field Formatted

In Hex view, data are showed up in hexadecimal format. The data collected from DP_WS is shown below in Figure 4-16.

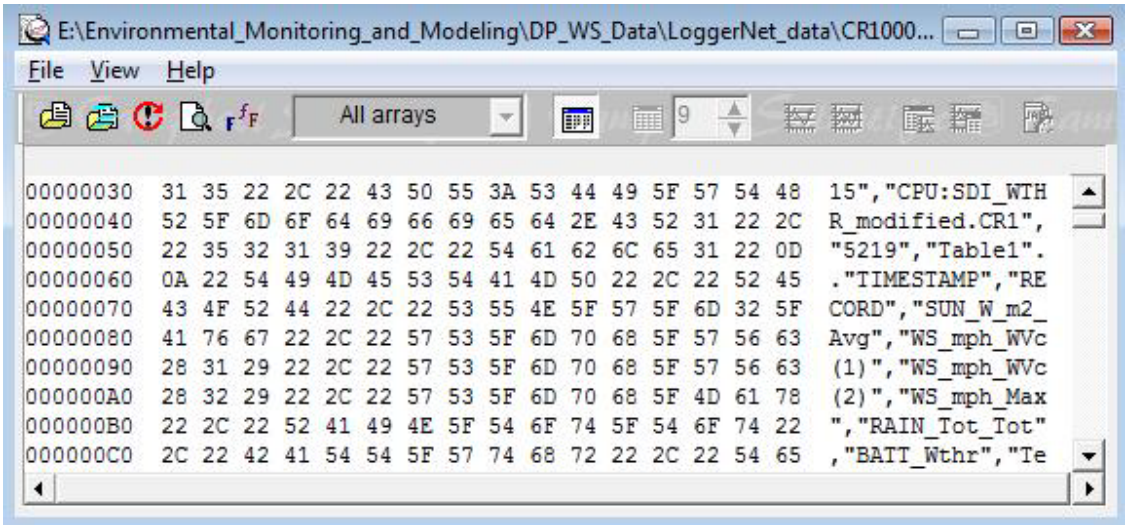


Figure 4-16 Hex View-Hexadecimal Format

PC208W Vs LoggerNet

Table 4-1 PC208W vs LoggerNet.

FEATURE	PC208W	LOGGERNET
Supported Campbell Scientific dataloggers	CR10X, CR10, CR500, CR510, 21X, CR7, CR23X	CR500, CR510, CR10, CR10X, 21X, CR23X, CR7, CR200/205, CR1000, CR3000, CR800, CR5000, CR9000
Programming language	Edlog	Edlog, CRBasic
Supported file types	.DLD, .CSI, .FSL, .PAR, .LBR, .PTI, .TXT, .DAT	.DLD, .CSI, .FSL, .PAR, .LBR, .PTI, .TXT, .PRN, .CSV, .LOG, .CR2, .CR5, .CR1, .CR3, .CR8, .CR9, .DAT
Program file to run datalogger	.CSI, .DLD	.CR1
Output file type	.DAT	.DAT
Program file creating options	Short Cut, Edlog	Short Cut, Edlog, CRBasic, Transformer Utility

4.2.4 Inter-connection of Datalogger and Nanostation2

This section includes short-term future work at DP_WS. Configuring the CR1000 datalogger is needed for making it possible communicates via ethernet port using a serial cable that connects PC COM port to CR1000 RS-232 port. IP address, subnet mask and IP gateway could be entered under TCP/IP tab which is displayed only when NL120 is connected with the datalogger. All these tasks can be done in Device Configuration Utility [22]. After this, the next step is to configure Loggernet to connect datalogger via the ethernet port. Input the datalogger's IP address and port number choosing IP port under Add Root tab of Loggernet Setup screen. The CR1000 default port number is 6785 which can be changed. Then add a PakBus port and set the desired baud rate. Add the datalogger (CR1000) and enter its PakBus address. Once the above settings are done, the datalogger can now be connected via ethernet port using LoggerNet connect screen and various tasks such as datalogger program transfer, editing datalogger programs, data collection etc. are possible [22].

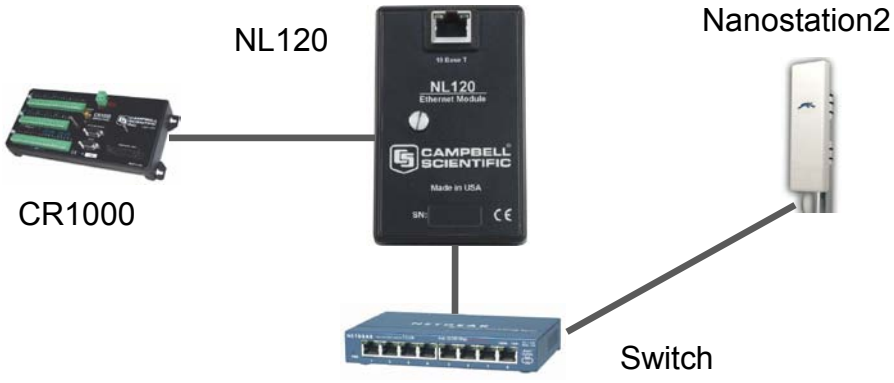


Figure 4-17 Inter-connections of Radio Equipments of DP_WS

Once the datalogger, NL120, and Loggernet have been setup as described above, communications are possible over TCP/IP. Ethernet interface NL120 can be connected with the CR1000 datalogger in DP_WS. Also a switch will be used for bridging the NL120 and the Nanostation2. A static IP address (129.120.9.228) will be set to the datalogger so that all the devices including the nanostations (EESAT_NS2 and DPWS_NS2) are in the same network domain. Once the switch is connected to the Nanostation2 and the datalogger via NL120, it will provide an internet connection to the datalogger via TCP/IP. Then the datalogger data can directly be accessible via HTTP web server. The picture shown above in Figure 4-17 is the connections of radio components (datalogger, Nanostation2 and switch) with the ethernet interface NL120 that will be used in DP_WS.

CHAPTER 5

WI-FI TECHNOLOGY AND RADIO WAVE PROPAGATION THEORY

In this chapter, some key facts about Wi-Fi technology and its theory focusing on 2.4 GHz Wi-Fi are discussed. A brief evolution of Wi-Fi is also discussed. Some advantages of Wi-Fi over other technologies are discussed particularly in this application. As the communication medium of Wi-Fi is the air, its performance obviously is affected with the characteristics of radio environment that encompasses air, and other obstacles such as tall buildings, trees, rain etc. A comprehensive focus on the theory of radio wave propagation is also discussed in this chapter. The discussion includes types and nature of radio wave propagation, radio signal interference in various channels especially in 2.4 and 5 GHz channels, hostile nature of radio environment and its influences in Wi-Fi operating frequencies and etc.

5.1 Wi-Fi Technology: Introduction

Wi-Fi is one of the latest and widely used unlicensed wireless technologies certified under IEEE 802.11 Standard in the world of wireless communication. Its operating frequencies are 2.4 GHz, 3.6 GHz and 5 GHz which fall under Ultra high frequency (UHF hereafter) (0.3-3.0 GHz) and Super high frequency (SHF hereafter) (3.0-30 GHz) frequency bands of electromagnetic spectrum [27]. Wi-Fi is becoming popular more and more since

last few years when 802.11b was first used in 1999 with 11 Mbps of maximum speed. With Wi-Fi, it is possible to create high-speed wireless local area networks (WLAN). Other WLAN technologies such as bluetooth, Worldwide Interoperability for Microwave Access (WiMAX) (IEEE 802.16), Wibree, Zigbee (802.15.4), Wireless Regional Area Networks (WRAN) (IEEE 802.22), Ultra wide band (UWB) (3.1-10.6 GHz), Near field communication (NFC) (13.56 MHz), Digital European cordless telephone (DECT) (1880-1900 MHz) and HomeRF shared wireless access protocol (SWAP) (2.4 GHz) etc. are also developing and growing fast to make their own place in the market [28].

5.1.1 History: Evolution of Wi-Fi

In the beginning, Wi-Fi was called “Hi-Fi” meaning High Fidelity. Later on August 1999, the term “Wi-Fi” was used officially for the first time. Unlicensed spread spectrum was first made available in US by the Federal Communications Commission (FCC) in rules adopted by May 9, 1985 and later FCC regulations were followed with some modifications in many other countries [29]. Nowadays Wi-Fi technology is widely used almost everywhere including laptops, PCs, smartphones, printers, and other peripherals. Before today, Wi-Fi traversed many IEEE standards with technical modifications.

802.11b was the first protocol of Wi-Fi released in 1999 and became the first widely accepted wireless networking standard. Transmitting at 11 Mbps of data rate, its operating frequency is 2.4 GHz. At the meantime, 802.11a was also developed with higher data rate, 54 Mbps which uses orthogonal frequency

division multiplexing (OFDM hereafter) modulation technique whereas 802.11b uses DSSS (Direct sequence spread spectrum) and CCK (Complementary code keying). Despite of its higher data rate, 802.11a could not reach up to that height where 802.11b has already started to establish its market because of its 5 GHz operating frequency. Because path loss at higher frequencies is huge, 802.11a couldn't sufficiently extend its mobility range as 802.11 did. Later in 2003, 802.11g came with higher data rate (54 Mbps) which uses OFDM modulation technique and operates in 2.4 GHz frequency band. Then most dual-band 802.11a/b products became dual-band/tri-mode, supporting 802.11a and 802.11b/g in a single mobile adapter card or access point. Now there is a new 802.11n protocol proposed recently which operates in 2.4 GHz and/or 5 GHz at a speed of 600 Mbps. This protocol is supposed to be released in September 2009. This protocol has its maximum throughput of 144 Mbps. This new 802.11n protocol uses three CCK, DSSS and OFDM modulation techniques. The comparison table of above discussed various IEEE 802.11 protocols is given below in Table 5-1 [29].

Table 5-1 IEEE standards: Comparison.

IEEE Standard	802.11a	802.11b	802.11g	802.11n
Operating frequency	5 GHz	2.4 GHz	2.4 GHz	2.4 or 5 GHz
Net Bit Rate (max)	54 Mbps	11 Mbps	54 Mbps	600 Mbps
Throughput (typical)	27 Mbps	5 Mbps	22 Mbps	144 Mbps

Modulation Technique	OFDM	CCK or DSSS	CCK, DSSS or OFDM	CCK, DSSS or OFDM
Channel Bandwidth	20 MHz	22 MHz	22 MHz	22 or 20 MHz
Range (Indoor)	35 m	38 m	38 m	70 m
Release Date	1999	1999	2003	Not released

5.1.2 Advantages and Challenges of Wi-Fi

Advantages:

Wi-Fi, one of the WLAN technologies, allows users to connect two or more computers or devices using DSSS or OFDM modulation technique within a limited area without the need of using cables. Because Wi-Fi uses an unlicensed radio spectrum, it has become very popular in houses, offices, universities and other places because of its mobility and ease of installation. This feature allows users to move around freely and remain connected to the network. These days, most of the laptops come with built-in Wi-Fi card. Wi-Fi has a set of global standards. Unlike cellular carriers, Wi-Fi users can work in different countries around the world at all time.

Challenges:

Interference is the main challenge of Wi-Fi system. The use of Wi-Fi is totally free which allows any one to use it anywhere without any regulatory approval. So this allows interference to occur very easily within Wi-Fi users using the same frequency band. In order to control the rapidly increasing interference,

there is a regulatory limit set for all devices to stay under 100 mW of output power [30]. This confines the range of transmission, which may be troublesome in many applications where range is important. The 2.4 GHz Wi-Fi users are even more prone to interference because they suffer interference not only from other Wi-Fi users but also from other technologies sharing the same frequency spectrum such as , microwave ovens, cordless phones, wireless transmitters such as baby monitors and etc. So Wi-Fi has a great challenge to overcome this drawback to improve system performance.

Wi-Fi power consumption is quite higher as compared to other technologies. Speed of Wi-Fi typically ranging from 2 Mbps to 54 Mbps is relatively slower than that of the slowest common 100 Mbps wired LAN. One of the encryption methods called WEP (Wired equivalence privacy) has been shown to be breakable. So access points can be used to steal important and personal information transmitted via Wi-Fi users.

5.1.3 Wi-Fi Channels

Wi-Fi works on three different frequency spectrums which are 2.4 GHz, 3.6 GHz and 5 GHz. Wi-Fi 802.11a operates on 5 GHz band, Wi-Fi 802.11b and 802.11g operate on 2.4 GHz and Wi-Fi 802.11n on both 2.4 and 5 GHz band. Wi-Fi 802.11y operates on 3.6 GHz [31-33]. Among these three channels, 2.4 GHz is the most popular and widely used Wi-Fi band. This band of operation is an unlicensed band and hence free to use anywhere and by anyone. Because 2.4

GHz band is open for use globally without having to have license to operate, the devices that use Wi-Fi such as laptops can be used anywhere in the world.

i) Wi-Fi in 2.4 GHz

The IEEE Standards that use 2.4 GHz band are 802.11b, 802.11g and 802.11n. The operating range for 2.4 GHz band is 2.4-2.4835 GHz (2400-2483.5 MHz). This total of 83.5 MHz of Industrial, scientific and medical (ISM hereafter) band is divided into 14 channels which are separated by 5 MHz (with the exception of 12 MHz separation between channel 13 and 14). The graphical representation of Wi-Fi channels in 2.4 GHz band is shown in Figure 5-1. As specified by 802.11 WLAN standards, the channel bandwidth is 22 MHz. But the channel separation for 2.4 GHz Wi-Fi is only 5 MHz although the specified standard is 25 MHz [32-35].

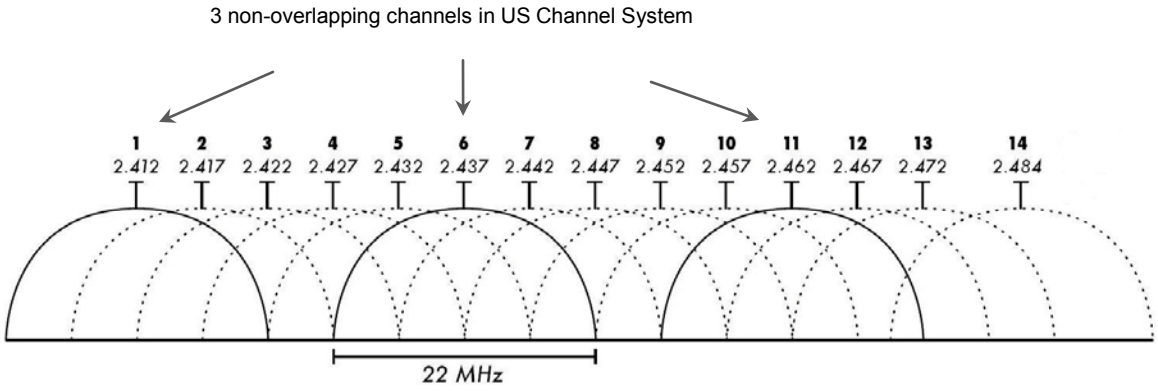


Figure 5-1 2.4 GHz Wi-Fi Channels

From the above Figure 5-1, it is clearly seen that the 14 channels occupy entire range of 802.11 Wi-Fi in 2.4 GHz band. The channel bandwidth is 22 MHz

and each channel is separated with its adjacent channel by 5 MHz except channel 14, which is separated from channel 13 by 12 MHz. The corresponding 14 frequencies are the central frequencies ranging from 2.412 GHz for channel 1 and 2.484 GHz for channel 14. In US channel system, there are three non overlapping channels: Channel 1, Channel 6 and Channel 11 whereas in Europe channel system, there are 4 non-overlapping channels: Channel 1, Channel 5, Channel 9 and Channel 13 [34]. But in practice, Europe also follows three non-overlapping channel system. Table 5-2 shows channel allocation in 2.4 GHz.

Table 5-2 2.4 GHz channel allocation.

Channel Number	Lower Frequency (MHz)	Center Frequency (MHz)	Upper Frequency (MHz)
1	2401	2412	2423
2	2406	2417	2428
3	2411	2422	2433
4	2416	2427	2438
5	2421	2432	2443
6	2426	2437	2448
7	2431	2442	2453
8	2436	2447	2458
9	2441	2452	2463
10	2446	2457	2468
11	2451	2462	2473
12	2456	2467	2478
13	2461	2472	2483
14	2473	2484	2495

Because every country has its own regulation, not all the 14 channels are allowed to use in all countries. Some countries have restrictions on some channels. For example, FCC in US allowed only 11 channels for use. This channeling system is also called North American System. That means the 3 channels are restricted to use by public in USA [35]. Similarly only 13 channels are allowed (1 channel restricted) in Europe. Japan allowed almost all of the 14 channels with the exclusion of that only 802.11b can be used in channel 14. Beside this, 13 channels are allowed to use in Europe and most of the world [32]. Table 5-3 shows channels allowed in 2.4 GHz in different countries.

Table 5-3 Channels allowed in 2.4 GHz band.

Channel Number	Center Frequency (MHz)	USA	Europe	Japan
1	2412	Yes	Yes	Yes
2	2417	Yes	Yes	Yes
3	2422	Yes	Yes	Yes
4	2427	Yes	Yes	Yes
5	2432	Yes	Yes	Yes
6	2437	Yes	Yes	Yes
7	2442	Yes	Yes	Yes
8	2447	Yes	Yes	Yes
9	2452	Yes	Yes	Yes
10	2457	Yes	Yes	Yes
11	2462	Yes	Yes	Yes
12	2467	No	Yes	Yes
13	2472	No	Yes	Yes
14	2484	No	No	802.11b only

ii) Wi-Fi in 3.6 GHz

The IEEE Standard that uses 3.6 GHz band is 802.11y approved on September 2008. Unlike other Wi-Fi, this Wi-Fi is not the unlicensed one, licensees have to pay a small fee for a nationwide and also they have to pay additional fee for each high powered base station that they deploy[31]. It is not as popular as other two 2.4 GHz and 5 GHz Wi-Fi, but it operates at much higher power allowing greater transmission range. The operating frequency range for 3.6 GHz band is 3.65-3.7 GHz (3650-3700 MHz). The channel separation can be 5 MHz, 10 MHz or 20 MHz. Some of its applications include back haul Wi-Fi networks, fixed point to point links, fixed point to mobile links etc [31, 36].

iii) Wi-Fi in 5 GHz

The IEEE Standards that use 5 GHz band are 802.11a, 802.11j, 802.11h and 802.11n. Though the operating range extends within 5.15-5.825 GHz, the 5 GHz band is divided into three separate 100 MHz sections. The "low" band ranges from 5.15-5.25 GHz, the "middle" from 5.25-5.35 GHz and the "high" band from 5.725-5.825 GHz. The upper portion of this band is restricted almost everywhere in the world. There are 23 non-overlapping channels (allowed in US) each of which are separated by 20 MHz. A list of allowed and restricted 5 GHz channels in different parts of the world is shown in Table 5-4. Although 802.11a was ratified at the same time (1999) as 802.11b, it could not catch people's attention in the same way 802.11b did despite of the fact that it offered a much higher data rate. One of the main reasons behind this was that it operated in 5

GHz ISM band, which made the chips more expensive. Another reason is the shorter transmission range because of higher frequency. However, this band is very appropriate when high performance is required [29, 32-33, 37-38].

Table 5-4 Channels allowed in 5 GHz band.

Channel	Center Frequency (MHz)	USA (20 MHz)	Europe (20 MHz)	Japan (20 MHz)
183	4915	No	No	No
184	4920	No	No	Yes
185	4925	No	No	No
187	4935	No	No	No
188	4940	No	No	Yes
189	4945	No	No	No
192	4960	No	No	Yes
196	4980	No	No	Yes
7	5035	No	No	No
8	5040	No	No	No
9	5045	No	No	No
11	5055	No	No	No
12	5060	No	No	No
16	5080	No	No	No
34	5170	No	No	No
36	5180	Yes	Yes	Yes
38	5190	No	No	No
40	5200	Yes	Yes	Yes
42	5210	No	No	No
44	5220	Yes	Yes	Yes
46	5230	No	No	No
48	5240	Yes	Yes	Yes
52	5260	Yes	Yes	Yes
56	5280	Yes	Yes	Yes

60	5300	Yes	Yes	Yes
64	5320	Yes	Yes	Yes
100	5500	Yes	Yes	Yes
104	5520	Yes	Yes	Yes
108	5540	Yes	Yes	Yes
112	5560	Yes	Yes	Yes
116	5580	Yes	Yes	Yes
120	5600	Yes	Yes	Yes
124	5620	Yes	Yes	Yes
128	5640	Yes	Yes	Yes
132	5660	Yes	Yes	Yes
136	5680	Yes	Yes	Yes
140	5700	Yes	Yes	Yes
149	5745	Yes	No	No
153	5765	Yes	No	No
157	5785	Yes	No	No
161	5805	Yes	No	No
165	5825	Yes	No	No

2.4 GHz Wi-Fi Vs 5 GHz Wi-Fi

When comparing 2.4 GHz and 5 GHz Wi-Fi, the first few important things which are to be noticed are the throughput, mobility, interference etc. Since 5 GHz is greater than 2.4 GHz band, throughput is higher in 5 GHz band. The 2.4 GHz channel is widely used and also it has only 3 non overlapping channels and hence it is crowded too much. So the interference is quite severe in 2.4 GHz channel. The case of 5 GHz channel is different; many users do not use it and it has 23 non-overlapping channels. So even if there is interference in the channel selected for use, then one can move to different non-overlapping channel to

avoid or at least minimize the interference. Talking about the mobility, generally higher frequency application has relatively lower mobility than the smaller frequency application has. This is because 5 GHz signal covers a smaller transmission range than 2.4 GHz signal does. The rationale behind this is the higher the frequency, the lower is the transmission range because of the fact that Free space loss (FSL hereafter) is greater in higher frequencies. So 2.4 GHz offers better mobility [33, 37, 39-40].

Beside above-mentioned aspects, there are many other comparison criteria between them. One of them is the cost of operation, which is relatively higher in 5 GHz band because equipments of higher frequency (5 GHz) are costlier than of 2.4 GHz. The 2.4 GHz band is more widely used than the 5 GHz band. This allows 2.4 GHz compatible devices to interoperate with each other and other compatible devices while 5 GHz has a very limited interoperability within its own few 5 GHz compatible devices. However, now there are many frequency compatible devices available in the market.

Table 5-5 Comparison table: 2.4 GHz Wi-Fi Vs 5 GHz Wi-Fi.

FEATURE	2.4 GHz Wi-Fi	5 GHz Wi-Fi
IEEE Standards	802.11b/g/n	802.11a/n
Frequency Operating Range	2.4-2.4835 GHz	5.15-5.825 GHz
Data Rate (max.)	54 Mbps	~ 600 Mbps
Throughput (typ.)	27 Mbps	~ 144 Mbps
Range of Transmission	Longer	Shorter
Interference	Severe	Less severe

No. of Non-Overlapping Channels	3	23
Deployment Cost	Cheaper	Expensive
Channel Bandwidth	22 MHz	20 MHz
Channel Spacing	5 MHz	20 MHz
Entire band	83.5 MHz	675 MHz
Security	Fair	Good
Flexibility to deploy	High	Low
Signal adsorption	Low	High
Power Limits (directional ant.)	30 dBm	30 dBm
Power Limits (omni-directional ant.)	29 dBm	36 dBm (1 W)
Antenna gain limits (omni-directional ant.)	9 dBi	23 dBi
Interoperability	Higher	Lower

5.1.4 Interference in 2.4 GHz ISM Band

Any type of communication systems is subject to noise or interference. It is impossible to remove them completely, but of course could be tried to minimize them. Talking about Wi-Fi communication system, the more concerned is the interference rather than noise. Interference has been one of the main issues as well as challenges in the field of wireless communication. Depending upon the type of system, interference degrades the performance in a varying degree. Interference may occur when two different radio transmitters using the same frequency are located nearby or when an extraneous power is coming from a signal transmitting in an adjacent channel.

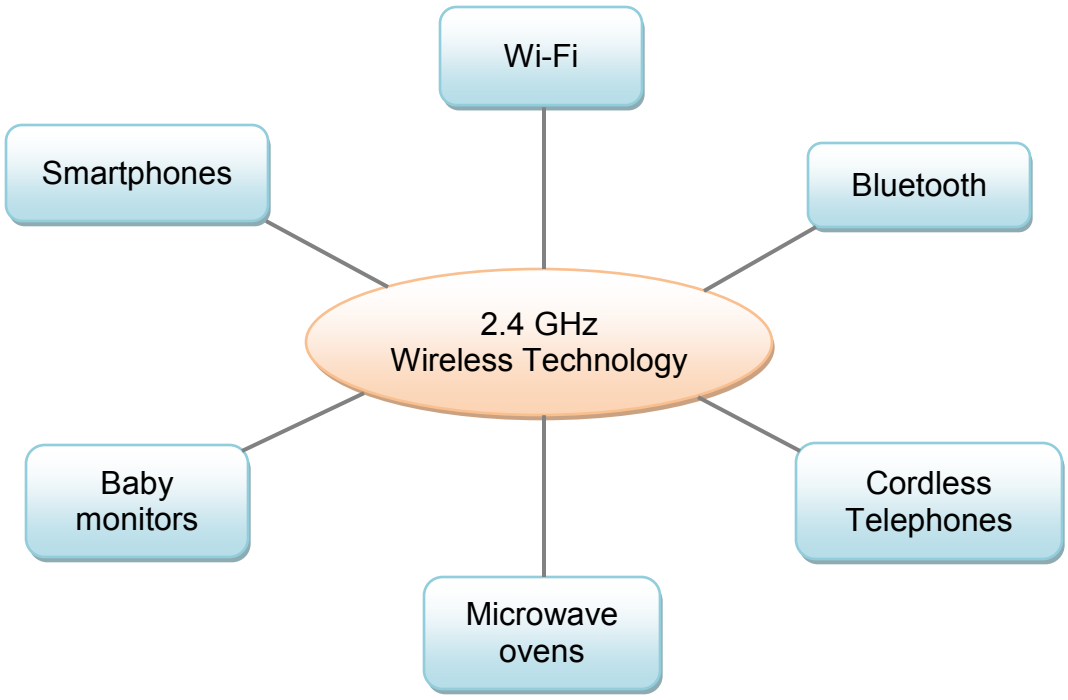


Figure 5-2 A Pictorial View of 2.4 GHz Technology Applications

As the 2.4 GHz ISM band is being more crowded day by day, interference in this band is rapidly increasing which is one of the biggest challenges today. The 2.4 GHz band is free to use, and the devices and equipments operates in this band are relatively cheaper than that of 5 GHz. This makes almost everyone choose this band for their different applications causing and receiving interference to and from each other. The widely used 2.4 applications are Wi-Fi 802.11b/g/n, Bluetooth, Microwave ovens, baby monitors, cordless telephones, etc. The above Figure 5-2 shows various types of applications that use 2.4 GHz wireless technology. One of the main interferers in 2.4 GHz is cordless phones, which are used in homes and offices. If at least one of these cordless phones is

in use in the same room where 802.11b/g WLAN is deployed, then you can notice the significant performance degradation in 802.11b/g. Also there's a signal degradation Despite of a very short range of Bluetooth, it affects its own system performance significantly as well as other systems nearby such as Wi-Fi [28, 33, 41].

5.1.5 Wi-Fi Vs other WLAN Technologies

Like Wi-Fi, there are other WLAN technologies such as GSM 900/1800, code division multiple access (CDMA hereafter), Bluetooth, hiperLAN, WiMAX, UWB, Zigbee, wibree, WRAN, DECT and HomeRF SWAP, universal mobile telecommunication system (UMTS) etc. But here, this thesis is focused on Wi-Fi versus cellular technologies such as global system for mobile communications (GSM hereafter), CDMA, UMTS etc. Depending upon the type of technologies used, different system has their own mobility range and speed. For example, cellular technologies such as GSM, CDMA, UMTS etc can cover a large distance whereas Wi-Fi, Bluetooth, etc. cover a very small range. But the speed at what Wi-Fi, Bluetooth etc. is relatively very high as compared to cellular technologies which have very low data transmission speed. So there is a trade of between speed and mobility. Figure 5-3 shows a graphical representation of Speed versus Mobility for different WLAN Technologies [29, 42].

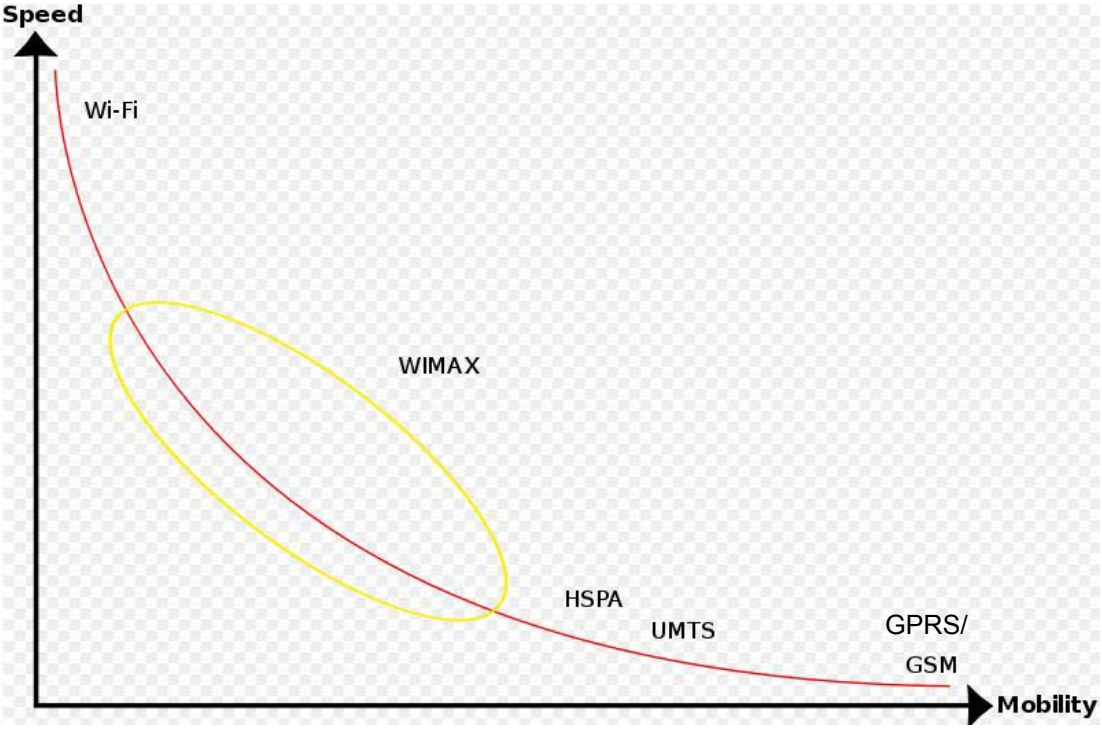


Figure 5-3 Speed Vs Mobility: WLAN Technologies

From the above figure, it can be noticed that Wi-Fi has the highest speed and lowest mobility range, GSM has the lowest speed but highest mobility range and W iMAX is the t rade o ff o f t hose t wo t echnologies. Other d issimilarities between Wi-Fi and cellular technologies are operating frequency bands, channel bandwidth, number of channels, modulation techniques etc. which are shown in the Table 5-6 below [29, 33, 43-45].

Table 5-6 Wi-Fi vs cellular technologies.

FEATURE	Wi-Fi Technology	GSM	CDMA
Standards	IEEE 802.11a/b/g/n	GSM900/1800	IS-95/CDMA2000
Frequency Operating band	2.4/5 GHz	900/1800/1900 MHz	900/1800/1900 MHz
Data Rate (max.)	600 Mbps	384 Kbps	1.23 Mbps
Transmission Range	15 km	35 km/25 km	25 km
Connectivity (while roaming)	Discrete	Almost continuous	Almost continuous
Channel Bandwidth	22 MHz	25 MHz/75 MHz	1.25 MHz
Channel Spacing	5 MHz	200 KHz	30 KHz
No. of Channels	14/42	124/374	Not fixed
Modulation Technique	FHSS/DSSS/OFDM	GMSK	Spread Spectrum
Application	Wireless networking	Cellular	Cellular
License Regulation	Unlicensed	Licensed	Licensed
Interference	Severe	less severe	Depends on no .of users
Flexibility to deploy	High	Lower	Lower
Interoperability	Higher	Lower	Lower

5.1.6 Advantages of Wi-Fi Technology over GPRS Technology

There are several advantages of Wi-Fi over GPRS technology. That's why a modern Wi-Fi technology is used in the present application (for DP_WS) instead of GPRS technology. Using Wi-Fi technology instead of GPRS, the same task can be done more easily and more reliably at much higher speed. Also, Wi-

Fi can support a lot of other applications which could not be achieved using GPRS such as applications requiring higher data rates. And obviously, use of Wi-Fi technology is free.

Table 5-7 Wi-Fi vs GPRS technology.

FEATURE	Wi-Fi Technology	GPRS Technology
Standards	IEEE 802.11a/b/g/n	GPRS
Operating frequency band	2.4/5 GHz	900/1800/1900 MHz
Data Rate (max.)	600 Mbps	171.2 kbps
Throughput (typical)	27 Mbps @ 802.11g	15-40 kbps
Typical Transmission Range	5 km	25 km
Channel Bandwidth	22 MHz	200 kHz
Channel Separation	5 MHz	200 kHz
Maximum power consumption	5 W	2 W
No. of Channels	14/42	124/174
Modulation Technique	FHSS/DSSS/OFDM	GMSK
License Regulation	Unlicensed	Licensed
Interference	Severe	Not severe

Table 5-7 [29, 45-47] shows some of the key differences between Wi-Fi and GPRS technologies.

5.2 Radio Wave Propagation Theory

Radio signals are affected in many ways by objects in their path or/and by the medium through which they travel. The way in which radio signals propagate may be the prime importance to anyone associated with radio communications, mobile telecommunications, Wi-Fi communications, satellite communications etc. It is even more important for the designers of above mentioned systems to know how the radio signals behave while propagating and what its impacts on system performance are because without knowing it, one cannot design a well functioned and reliable system. So it is extremely important to know radio wave propagation theory before designing and implementing any system in the real world.

Radio waves are electromagnetic waves occurring on the radio frequency portion of the electromagnetic spectrum [48]. Electromagnetic waves are self propagating waves consisting of electric and magnetic field components which oscillate in phase perpendicular to each other and also perpendicular to the direction of energy propagation. According to Maxwell's equation, a time-varying electric field generates a magnetic field and vice versa. Therefore, an oscillating electric field generates an oscillating magnetic field, the magnetic field in turn generates and oscillating electric field, and so on. These oscillating fields together form an electromagnetic wave [49]. The Figure 5-4 [50] shows a typical pictorial view of electromagnetic wave propagation in which blue and red waves denote magnetic and electric field respectively.

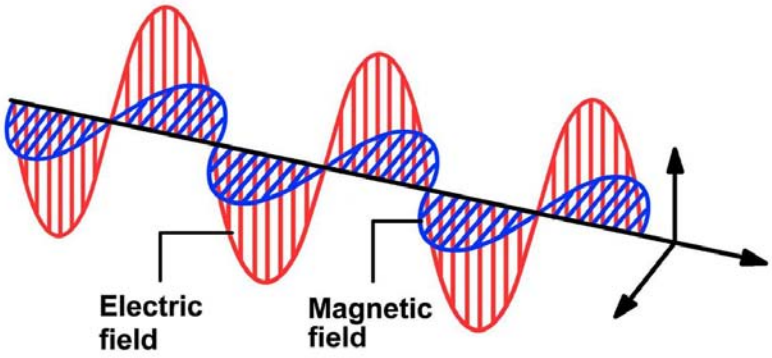


Figure 5-4 Electromagnetic Wave Propagation

Radio frequency spectrum ranges from 3 Hz-300 GHz which covers the lower boundary of extremely low frequency (ELF) and upper boundary of extremely high frequency (EHF). The Table 5-8 [27] given below shows the entire electromagnetic spectrum highlighting microwave frequency range. Within radio frequency range, radio wave occurring in ultra high frequency (UHF), SHF and EHF bands is called microwave. Microwave frequency (highlighted in shaded green color) ranging from 0.3 GHz to 300 GHz covers UHF, SHF and EHF bands of electromagnetic spectrum, however different sources use different boundaries for the lower band UHF and the upper band EHF. But in all cases microwave includes the entire SHF band (3-30 GHz) [27, 51]. All the Wi-Fi operating frequencies lie in UHF and SHF bands highlighted in blue color.

According to the wavelength or frequency of electromagnetic waves, they are classified into several types. Listing them according to descending order of wavelength (longer to shorter), they are as follows: radio waves, microwaves, infrared rays, visible light, ultraviolet rays, X-rays and gamma rays.

Table 5-8 Electromagnetic spectrum.

FREQUENCY	SYMBOL	WAVELENGTH	NAME
3-30 Hz	ELF	100-10 Mm	Radio Wave
30-300 Hz	SLF	10-1 Mm	
300-3000 Hz	ULF	1000-100 km	
3-30 kHz	VLF	100-10 km	
30-300 kHz	LF	10-1 km	
300-3000 kHz	MF	1000-100 m	
3-30 MHz	HF	100-10 m	
30-300 MHz	VHF	10-1 m	
300-3000 MHz	UHF	100-10 cm	Microwave
3-30 GHz	SHF	10-1 cm	
30-300 GHz	EHF	10-1 mm	
300-3000 GHz	FIR	1000-100 μm	Infra Red rays
3-30 THz	MIR	100-10 μm	
30-300 THz	NIR	10-1 μm	
400-790 THz		750-380 nm	Visible light
750-3000 THz	NUV	400-100 nm	Ultraviolet rays
3-30 PHz	EUV	100-10 nm	
30-300 PHz	SX	10-1 nm	X-rays
300-3000 PHz		1000-100 pm	
3-30 EHz	HX	100-10 pm	
30-300 EHz	Y	10-1 pm	Gamma rays

5.2.1 Types of Radio Waves

Radio waves propagating from transmitter to receiver undergo different kinds of phenomenon such as reflection, refraction, diffraction and scattering

before reaching the receiver. Not all the radio signals undergo all of the above-mentioned phenomenon, it depends upon the type of medium they are propagating and also the frequency of the propagating radio signal. Depending upon how the radio signals propagate, they are classified into following categories: direct waves, ground reflected waves, surface waves, sky waves etc. Direct and ground reflected waves are shown in Figure 5-5 whereas Figure 5-6 shows surface and sky waves

Direct Waves

Radio signals that travel along a straight path in a free space from transmitter (Tx) to receiver (Rx) are called direct waves or often called LOS signals. These waves are always supposed to be away from any obstacles in between Tx and Rx so it is only the transmission distance that affects these waves. Examples are satellite communication and microwave link point-to-point communication occurring in UHF, SHF and EHF bands.

Ground Reflected Waves

Radio signals that reach the receiver after getting reflected from the Earth's surface are called ground reflected waves. Even an LOS path has adequate Fresnel zone clearance, it may still suffer additional path loss other than that is occurred from straight transmission distance. This is the case of multipath propagation caused by ground reflection. In such type of LOS propagation, the two rays direct wave and ground reflected wave travel from Tx

to Rx reaching the receiver at different times with different amplitude and phase. So depending upon the relative amplitude and phase difference of the two propagated signals, the multipath propagation may result destructive or constructive path loss. More detail is discussed in two ray propagation model in Section 5.2.4 of this chapter [52].

Surface Waves

Radio signals that travel along the surface of the earth following its curvature till they reach their destination (receiver) are called surface waves. Lower frequencies, especially AM broadcasts in the medium wave (MF) and long wave low frequency (LF) bands travel efficiently as surface waves because these low frequency waves are more efficiently diffracted by the curvature of the Earth. Surface waves die more quickly as the frequency increases [53].

Sky Waves

Radio signals that are reflected back to earth surface by the ionosphere are called sky waves. Most long-distance high frequency (HF) radio communication between 3-30 MHz is a result of sky wave propagation. When radio waves reach the ionized layer of the ionosphere, refraction or bending of the wave occurs. The amount at what angle it gets refracted depends upon three things: the density of ionized layer (refractive index), the frequency of the radio wave and the angle at which the radio wave enters the layer (incident angle). When a radio wave strikes a thin, very highly ionized layer (low refractive index),

the wave may be bent back so rapidly that it will appear to have been reflected instead of refracted back to Earth [53].

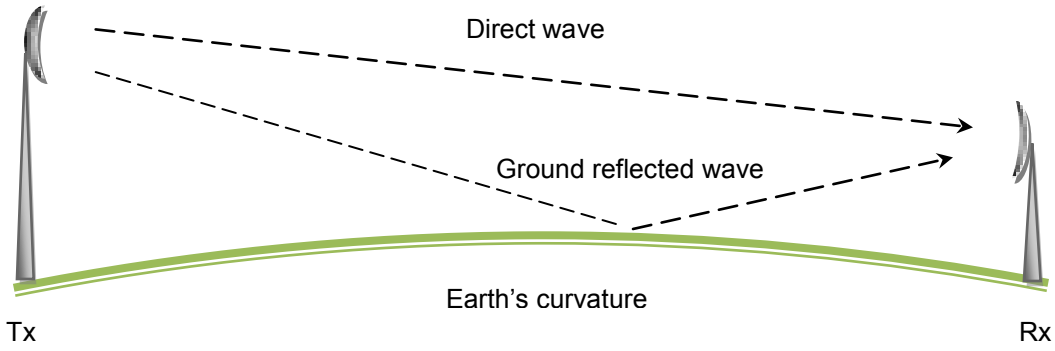


Figure 5-5 Radio Waves: Direct Wave and Ground Reflected Wave

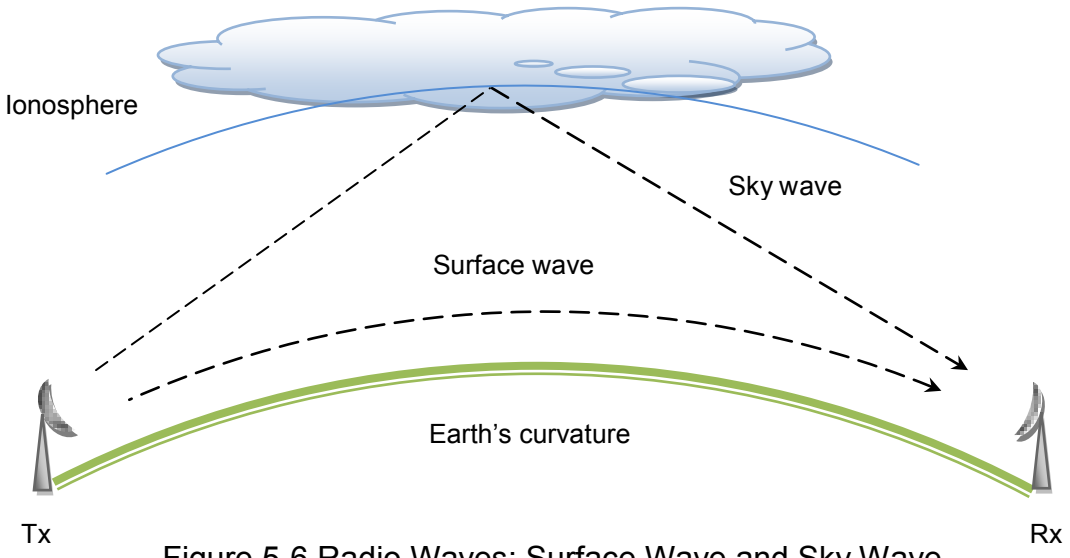


Figure 5-6 Radio Waves: Surface Wave and Sky Wave

5.2.2 Phenomenon of Radio Wave Propagation

Like light waves, radio waves are also electromagnetic waves and hence they are affected by different kinds of phenomenon such as reflection, refraction, diffraction, scattering and absorption. Understanding the effects of these phenomenon on the radio waves propagation has many practical applications such as designing a reliable mobile communication system, radio navigation, choosing appropriate frequencies for shortwave broadcastings etc.

Reflection

When radio waves traveling in a medium strike on any objects such as buildings, trees or surfaces such as ground, surface of sea etc. they are bounced back to the same medium with an alteration of 180 degree phase. This phenomenon is called reflection. The amount of reflection depends on reflecting material. Smooth metal surfaces of good electrical conductivity are very good examples of efficient reflectors of radio waves. Earth's surface and sea surface are also the good examples of good radio wave reflectors [54].

When radio waves are reflected from flat surfaces, there occurs a phase shift in the reflected wave. After reflection, the waves are approximately 180 degrees out of phase from their initial phase relationship. The radio waves that keep their phase relationships after reflection produce a stronger signal at the receiver and those that are received out of phase produce a weaker signal or fading signal. A reflection of very high frequency (VHF) and higher frequencies is important for radio transmission and for radar communication [54-55].

Refraction

When radio waves traveling in one medium enter into another medium, the bending of waves occur which is known as refraction of radio waves. After refraction, the velocity of the propagation changes. The velocity of radio waves is faster in rarer medium than in denser medium. The bending caused by the refraction is always towards the denser medium where the velocity of propagation is lower. One very important type of refraction of radio waves is atmospheric refraction where the radio waves get reflected back to the earth after entering into ionosphere as shown below in Figure 5-7. The reflection is actually caused by the refraction in the highly ionized layer of the atmosphere [54-56].

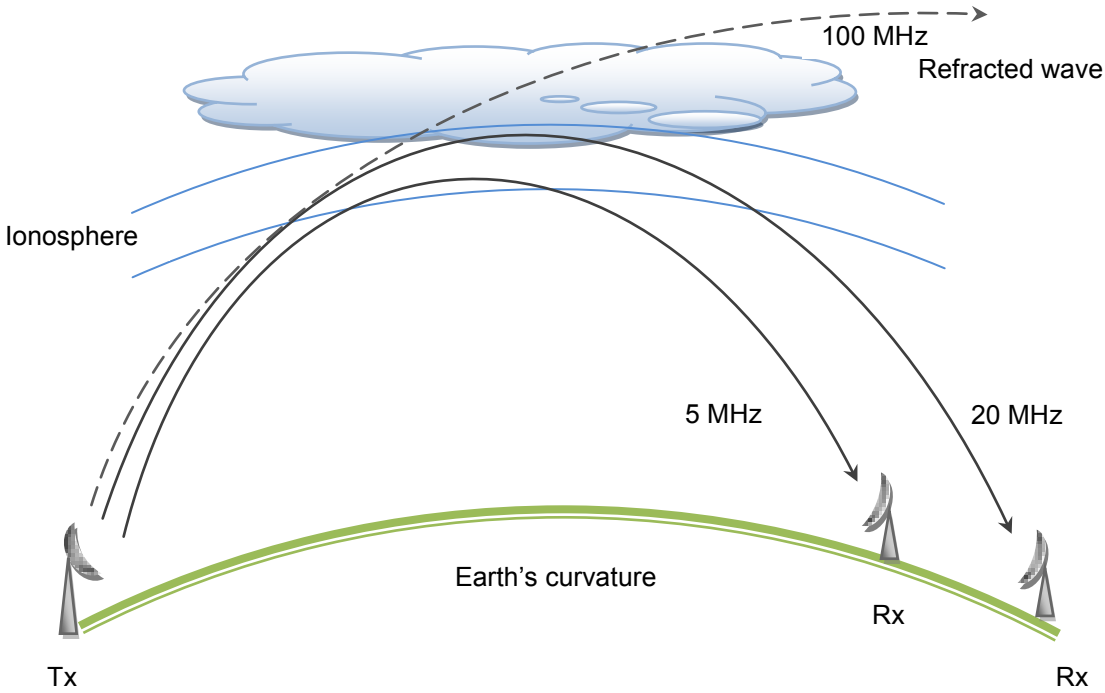


Figure 5-7 Ionospheric Refraction

Diffraction

When a radio wave meets an object of size comparable or smaller than the wavelength of the wave, it naturally tends to bend around the object due to which direction of part of wave energy is changed from the normal line of sight path. This bending phenomenon of wave is called diffraction of radio wave. Due to this change, energy can be received around the edges of the object. This means that a signal may be received from a transmitter even though it is shaded by large object between them. The ratio of signal strengths without obstacle and with obstacle is referred to as diffraction loss [56]. This phenomenon of radio wave is particularly noticeable in long wave broadcast transmissions. This diffraction phenomenon is used to send radio signal over a mountain range when a LOS path is not available.

Diffraction depends on the relationship between the wavelength and the size of the obstacle. Lower frequencies diffract around large smooth obstacle such as hill more easily than higher frequencies do. For example, in many cases where VHF (or higher frequencies) communication is not possible due to shadowing by hill, it is still possible to communicate using upper portion of HF band [52, 54, 56].

Scattering

When radio waves traveling in a medium strike on any objects such as particles, bubbles, droplets, surface roughness etc., then they are diffused or deflected in all direction from their straight trajectory. This phenomenon is called

scattering of radio waves. Scattering occurs when incoming signal hits an object whose size is in the order of the wavelength of the signal or less [57]. Scattered waves are produced by rough surfaces, small objects or by other irregularities in the channel.

Absorption

When radio waves traveling in a medium strike on any objects such as gas molecule, water particle etc., then they are absorbed by the objects in the medium. This phenomenon is called absorption of radio waves. Due to absorption phenomena the energy of a radio wave is absorbed when it propagates through the medium. Low frequencies (LF) radio waves travel easily through brick and stone, very low frequency (VLF) even penetrates sea-water. But as the frequency rises, absorption effect become more important and hence need to be taken into account while working with higher frequencies.

Absorption is often caused by atmosphere and hence atmospheric absorption is referred to as attenuation. One of the major causes of signal attenuation (atmospheric absorption) is the rain which affects significantly if the radio wave frequency is greater than 10 GHz. Other atmospheric phenomena that causes absorption of a radio wave are snow, fog, cloud etc [56]. So this phenomenon is one of the major concerns in microwave communication when operating in higher frequencies.

5.2.3 Polarization of Radio Wave

Property of radio waves that describes the orientation of their oscillations while moving towards the direction of energy propagation is known as polarization [58]. The plane of polarization of radio waves is the plane in which the electric field (E-field) propagates with respect to the Earth. Radio waves polarization is perpendicular to the wave's direction of travel which is characteristics of transverse wave. On the basis of the direction in which the radio waves move, the polarization can be classified into two types: linear polarization and circular or elliptical polarization [59].

Linear Polarization

The polarization of wave in which electric field is oriented in a single direction as the wave travels is called linear polarization. The wave can be thought of as vibrating in one plane either up and down or side to side. Linear polarization can be further classified into two types which are vertical and horizontal polarizations [58].

- *Vertical polarization:* The polarization where the E-field component of the radiated wave propagates in a plane perpendicular to the Earth's surface is called vertical polarization and such a radiation is said to be vertically polarized [59].

- *Horizontal p olarization:* The pol arization where t he E -field c omponent propagates in a pl ane par allel t o t he E arth's surface i s called horizontal polarization and such a radiation is said to be horizontally polarized [59].

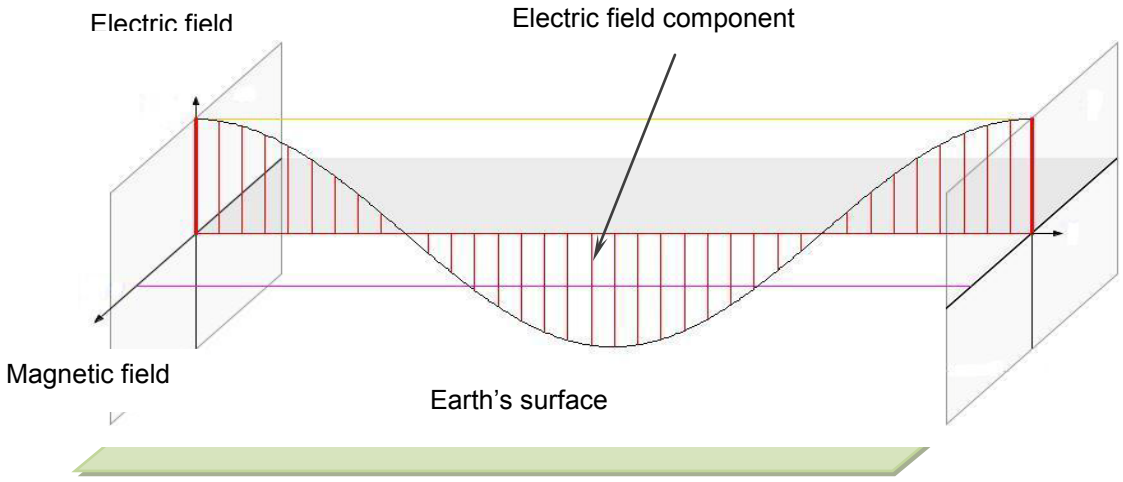


Figure 5-8 Vertical Polarization

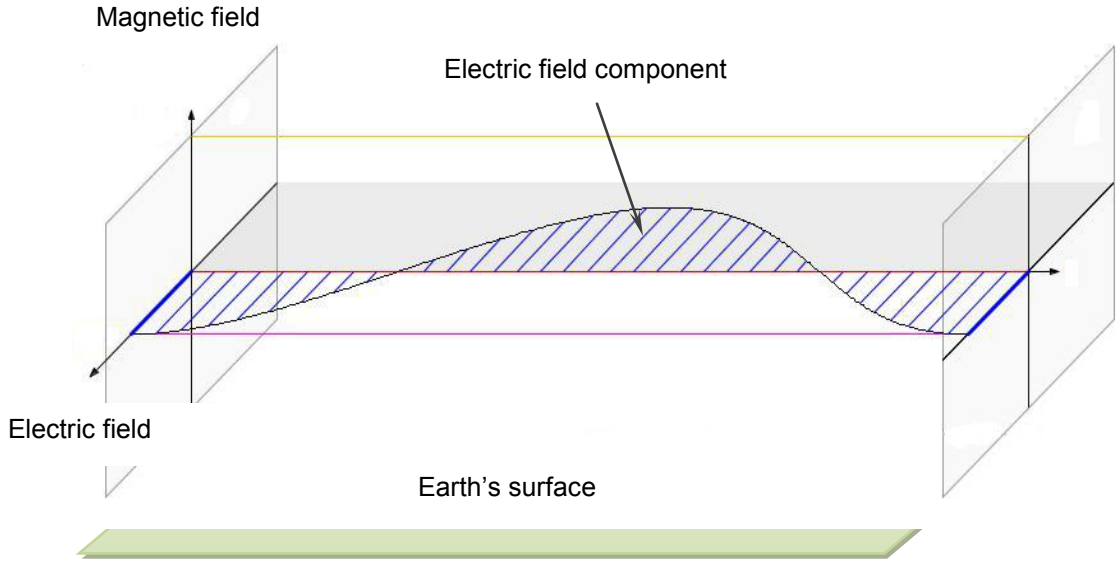


Figure 5-9 Horizontal Polarization

- *Circular or elliptical polarization:* When radio waves propagate, electric field may rotate rightward or leftward in the direction of propagation. This type of polarization is called circular or elliptical polarization. Circular polarization can be thought of as a signal propagating from an antenna that is rotating [58].

The choice of polarization may play a vital role in some applications. This means there is performance difference of type of polarization on type of applications. For example in some applications, horizontal polarization best suits while vertical polarization may be the best choice in another application. While medium wave broadcast stations generally use vertical polarization because ground wave propagation is considerably better using vertical polarization rather than using horizontal polarization, horizontal polarization proves to be best fit for long distance communications where ionospheric reflections take place. Circular polarization is appropriate choice in satellite communications [60].

Polarization is very important factor in radio wave communication. In order to get the good reception at the receiver site, it is always needed to match the polarization of transmitting and receiving antennas. In many applications, one the signal has been transmitted, polarization will remain normally the same. However, polarization can be slightly changed by the influence of reflections from the objects in the path. Reflections from ionosphere can cause a greater change in the polarization. A new technology called adaptive antenna polarization (AAP) has already been introduced in the market. With the advent of this technology,

the undesired fluctuation of polarization of the radio waves can be minimized and controlled to some extent.

5.2.4 Radio Wave Propagation Models

Radio wave propagation model is an empirical mathematical formulation for the characterization of radio wave propagation. It describes mathematically how the radio waves propagate, how they reach up to receiver, which paths do they follow and etc. And by knowing these factors, one can set the parameters accordingly and predict out the receive power by using the appropriate radio wave propagation model. There are basically two propagation models: Free space propagation model and two-ray propagation model [61].

Free Space Propagation Model

The term "free space" here is the space or path between transmitting antenna (Tx) and receiving antenna (Rx) where there is supposed to be nothing (obstacle) and hence the radio wave can travel freely without being obstructed by any obstacle or influenced by any phenomena like reflection, refraction, diffraction etc. In another word, we can say free space propagation is a LOS propagation. So it is only the Tx-Rx distance that influences the receive signal strength at the receiving site. Satellite communication system and microwave LOS radio links undergo free space propagation.

The free space propagation model is used to predict received signal strength when the LOS path between Tx and Rx is clear.

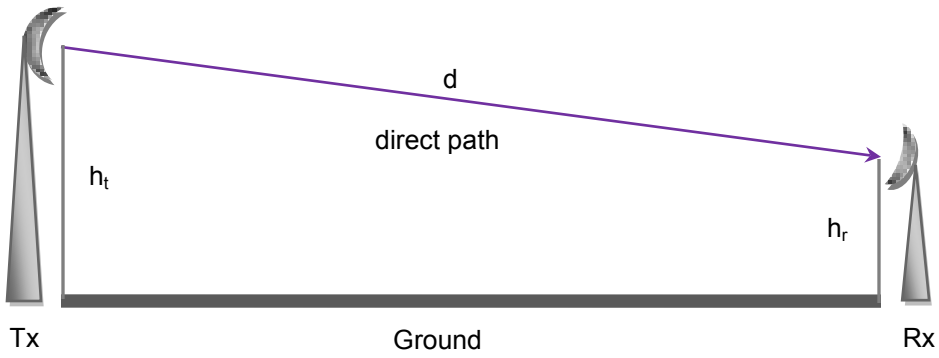


Figure 5-10 Free Space Propagation Model

A schematic diagram of free space propagation model is shown in above Figure 5-10 where d is the direct path distance and h_t and h_r are the heights of transmitting and receiving antenna respectively. The receive power Pr (dB) of the signal at the receiving site is given by the formula [62] known as Friis transmission formula which is as follows:

$$P_r(d) = \frac{P_t G_t G_r \lambda^2}{(4\pi)^2 d^2} \quad \text{..... Equation 5-1}$$

where,

P_t = Transmitted power of the signal

G_t = Transmitting antenna gain

G_r = Receiving antenna gain

d = distance between Tx and Rx antenna

λ=wavelength of the propagating signal

Expressing the above expression in logarithmic form, we get,

$$P_r(dBm) = P_t(dBm) + G_t(dB) + G_r(dB) - FSL(dB)$$ ..... Equation 5-2

where,

P_t = Transmitted power of the signal in dBm

G_t = Transmitting antenna gain in dB

G_r = Receiving antenna gain in dB

FSL = Free Space Loss in dB

Inverse square law states that the power density of an electromagnetic wave at a point is proportional to the inverse of the square of the distance from the source. Let P_1 be the power distributed over a large spherical surface area at a distance r from the transmitting source, then power density or signal strength is given by [63]

$I_r = \frac{P_1}{A_1} = \frac{P_1}{4\pi r^2}$ where $A=4\pi r^2$ is the surface area of sphere of radius r

$$I_r \propto \frac{1}{r^2} \quad \text{-----} \quad \text{(i)}$$

Let's double the distance so that we have a new distance 2r, then

$$I_{2r} \propto \frac{1}{(2r)^2} \longrightarrow I_{2r} \propto \frac{1}{4r^2} \quad \text{-----} \quad \text{(ii)}$$

From (i) and (ii), we have, $I_{2r} = \frac{1}{4} I_r$ ----- (iii)

From (iii), it is clearly noticeable that, when we double the distance, then the signal strength will be reduced to one-quarter of its original value. Note that

the signal strength is watt per unit area. But it's very easy to do this type of power calculation in logarithmic expression or in dB unit.

From (iii), changing in dB unit, we have

$$I_{2r}(dB) = 10\log\left(\frac{1}{4}I_r\right) = 10\log\left(\frac{1}{4}\right) + 10\log(I_r) = I_r(dB) - 6.0206 \quad \text{----- (iv)}$$

So it is seen that the signal strength at double distance is 6 dB less than the original strength.

Using Equation 5-2, Table 5-9 given below shows the theoretically calculated values of receive signal level (RSL hereafter) at various distances varying transmit powers for 2.4 GHz radio signal. The calculations assumed the transmit and receive antenna are of 10 dBi antenna gain. The calculations are done in logarithmic units. The Eq. 5-2 is used for the calculation of RSL.

Table 5-9 Tx power vs RSL for 2.4 GHz.

Tx power (dBm)	Receive Signal Level - RSL (dBm)			
	d = 1 km	d = 5 km	d = 20 km	d = 50 km
1	-79.05	-93.03	-105.75	-113.03
2	-78.05	-92.03	-104.75	-112.03
5	-75.05	-89.03	-101.75	-109.03
10	-70.05	-84.03	-96.75	-104.03
25	-55.05	-69.03	-81.75	-89.03
50	-30.05	-44.03	-56.75	-64.03
100	19.95	5.97	-6.75	-14.03

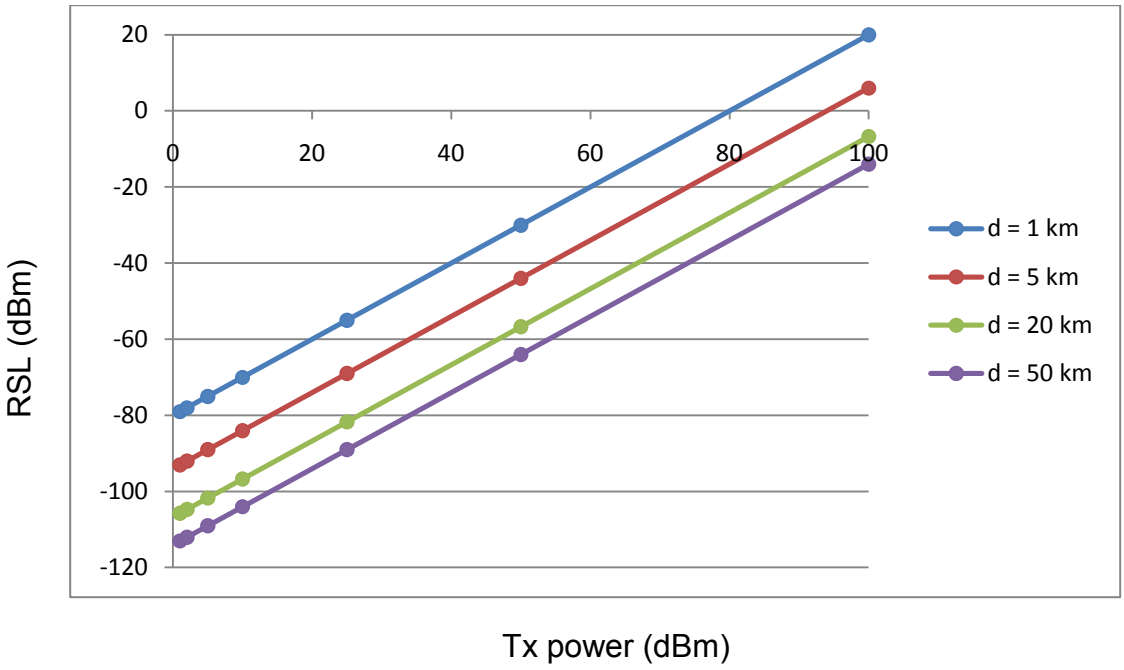


Figure 5-11 Tx Power Vs RSL for 2.4 GHz

The above Figure 5-11 is the plot of Tx power Vs RSL referring to the data shown in Table 5-9. The four different colors represent the RSL lines at four different distances. Blue denotes the line for 1 km, brown for 5 km, green for 20 km and violet for 50 km. From the graph, it is implied that the RSL lines are linearly increasing with the Tx power.

Another important thing that can be inferred from the above graph is that the RSL value will go on increasing as the Tx-Rx distance becomes closer and vice versa.

Two-Ray Propagation Model

In real world situation, it is not always true to say that there exists only one clear LOS path between transmitter and receiver. In fact, this condition is very rare and most of the time, there exists two radio paths which are direct LOS path and ground reflection path. Unlike free space propagation model, the two-ray propagation model considers both the direct LOS path and ground reflection path while calculating the receive power at the receiver. This model gives more accurate prediction for long distance propagation than free space model [52, 55, 64]. So for this model, it is not only the Tx-Rx distance that influences the receive signal strength but also is the signal reflected from the ground. Many radio communication systems and microwave LOS radio links where transmission distance is long, follow this model. The Figure 5-12 shows a schematic diagram of a two ray propagation model.

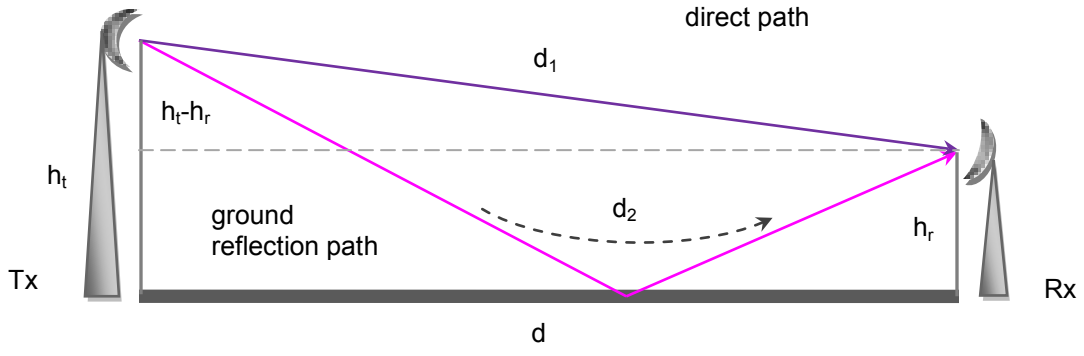


Figure 5-12 Two-Ray Propagation Model

The direct (d_1) and ground reflected (d_2) paths are denoted by violet and pink respectively. h_t and h_r are the heights of Tx and Rx antenna. The received power is given by Equation 5-3 [65-66].

$$P_r(d) = \frac{P_t G_t G_r h_t^{\,2} h_r^{\,2}}{d^4 L} \quad \text{..... Equation 5-3}$$

It can be shown that the receive power decreases by 12 dB/octave or 40 dB/decade. That means when the transmission distance is doubled, the receive power decreases by 12 dB and when the distance is made 10 times greater, it decreases by 40 dB [55].

Path and Phase Difference

Path difference is the difference in path length between the direct and reflected signal. From the above Figure 5-12, the path difference (Δd) between direct and ground reflected paths can be expressed as follows [66]:

$$\Delta d = d_2 - d_1 = \sqrt{(h_t + h_r)^2 + d^2} - \sqrt{(h_t - h_r)^2 + d^2}$$

when $d >> h_t + h_r$, then using Taylor series approximation, the above expression can be approximated as

$$\Delta d = d_2 - d_1 \approx \frac{2 h_t h_r}{d}$$

Phase difference ($\Delta\theta$) is the difference in phase of the two (direct and ground reflected) paths given by the following formula [66]

$$\Delta\theta = \frac{2\pi\Delta}{\lambda} = \frac{\Delta\omega_c}{c}$$ where w_c is the angular frequency of the signal

5.2.5 Path Loss

Path loss is the reduction of signal strength of an electromagnetic wave as it propagates through the medium. In wireless communication, the term 'medium' refers to space between Tx antenna and Rx antenna. Path loss is very important element in the design of any radio communication systems or wireless system. Path loss determines many other elements of the system such as Tx power, frequency of operation, antenna size, antenna gain, antenna height and also receiver sensitivity etc. So it is very important to figure out the causes of path loss and calculate how much path loss will occur for a given system.

To calculate the total path loss, it's worthwhile to find out its individual contributors which collectively form path loss. Some major constituents of path loss free space loss, attenuation, multipath fading, diffraction loss etc. Friis transmission formula given by the Equation 5-2

$$P_r(dBm) = P_t(dBm) + G_t(dB) + G_r(dB) - FSL(dB)$$

is a formula to predict receive power in an ideal condition where there are no other losses except FSL. But in practical we do have a lot of other losses also beside FSL. So Equation 5-2 can be rewritten as

$$P_r(dBm) = P_t(dBm) + G_t(dB) + G_r(dB) - Path\_loss(dB) \quad \text{..... Equation 5-4}$$

where path_loss(dB) is the total losses occurred while propagating from Tx to Rx given by the following expression

$$Path\_loss = FSL(dB) + A(dB) + L_{mf}(dB) + L_{dif}(dB) + L_{tl}(dB) \quad \text{..... Equation 5-5}$$

where,

FSL = Free Space Loss

A = Attenuation

L_{mf} = Loss due to multipath fading

L_{dif} = Loss due to diffraction

L_{tl} = Loss due to transmission line between Tx/Rx and Tx/Rx antenna

Free Space Loss

Free space loss (FSL) is the loss in signal strength of a transmitted signal resulting from the distance covered while travelling from Tx to Rx over a line of sight path. It is directly dependent upon two factors, the first is the distance between Tx and Rx and the second is the frequency of operation. This means as you increase frequency, the FSL will also increase accordingly and vice versa. Similarly, when the Tx-Rx distance is increased, the FSL also increases and vice versa. The free space loss is given by the following formula [67]:

$$FSL = \left(\frac{4\pi d}{\lambda}\right)^2 \quad \text{..... Equation 5-6}$$

The Equation 5-7 given below is the logarithmic form of above Eq. 5-6.

$$FSL(dB) = 20\log(f) + 20\log(d) + 32.45 \quad \text{..... Equation 5-7}$$

where,

f = frequency of the signal (MHz)

d = distance between Tx and Rx (km)

From the above equation of free space loss, it can easily be shown that if we double the transmission distance (d), keeping everything else (frequency) unchanged, FSL will be 6 dB more.

For example, for a distance of d, let's rewrite the Equation 5-7 as

$$FSL(dB)_d = 20\log(d) + K \quad \text{-----} \quad \text{(v)}$$

where K = 32.45+20log(f) = constant

Now on doubling the frequency and keeping everything else unchanged, we'll have FSL at distance 2d given by,

$$FSL(dB)_{2d} = 20\log(2d) + K \quad \text{-----} \quad \text{(vi)}$$

$$FSL(dB)_{2d} = 20\log(d) + K + 20\log(2)$$

$$FSL(dB)_{2d} = 20\log(d) + K + 6.0206$$

So from (v), replacing 20log(d)+K by $FSL(dB)_d$, we get

$$FSL(dB)_{2d} = FSL(dB)_d + 6.0206 \quad \text{..... Equation 5-8}$$

So it can be concluded that the relationship between the path loss and the transmission distance is such that the path loss increases by 6 dB /octave. Similarly, it can also be shown that the path loss increases by 20 dB /decade which is equivalent to 6 dB/octave.

Path Loss Vs Distance (for 2.4 GHz and 5 GHz)

Since the path loss is one of the major reasons that influences the receive power at the receiving site, it's important to know at what conditions the path loss is greater and how it can be minimized. One of the parameters that directly influence the path loss is the frequency of operation. So it's also important to know how the various frequency bands affect the path loss. The Table 5-10 below shows the theoretically calculated path loss values at various transmission distances for 2.4 GHz and 5 GHz frequency bands. The table is calculated using the formula for path loss given by Equation 5-7.

Table 5-10 Path loss vs transmission distance.

Transmission distance (km)	Path Loss/FSL (dB)	
	2.4 GHz	5 GHz
0.5	94.03	100.41
1	100.05	106.43
2	106.07	112.45
3	109.6	115.97
5	114.03	120.41
8	118.12	124.49
10	120.05	126.43
15	123.58	129.95
25	128.01	134.49
50	134.03	140.41
100	140.05	146.43

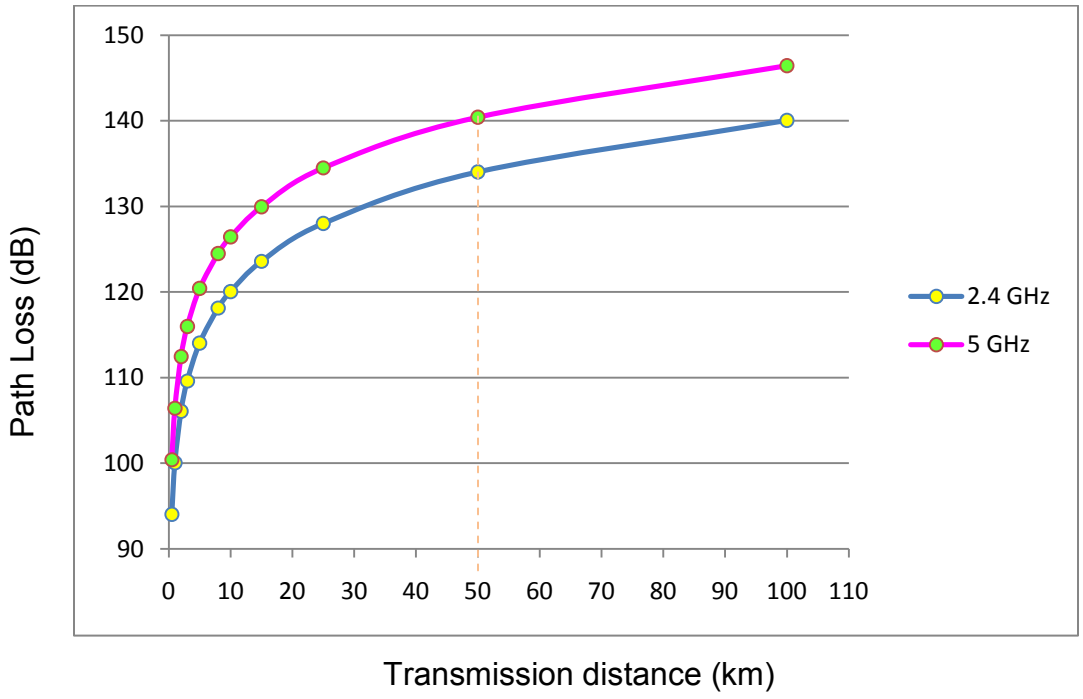


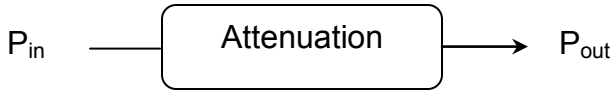
Figure 5-13 Path Loss Vs Transmission Distance

Above Figure 5-12 is the plot of path loss Vs transmission distance referring to the Table 5-9. From the graph, it is seen that the loss is increasing as the transmission distance increases but it is not linear. The rate of increment of loss is higher in lower distances than in greater distances. As the transmission distance goes on increasing the path loss tends to saturate. Also, it is seen that the path loss at every distance is relatively higher in 5 GHz than in 2.4 GHz. For example, the path losses for 2.4 and 5 GHz are 134.03 dB and 140.41 dB at 50 km. So, it can be inferred from the table and the graph that the path loss at 5 GHz is always (every distance) about 6 dB more than at 2.4 GHz. The pink line denotes the 5 GHz line and blue the 2.4 GHz.

Signal Attenuation

The loss of signal strength due to atmospheric absorption during transmission as it propagates through a medium is referred to as attenuation. Attenuation does not include the FSL. Attenuation is measured in dB or more precisely dB/km. During transmission, the signal gets attenuated exponentially with the distance it traverses. In some applications (especially applications requiring higher frequencies or in which signal has to travel through the medium where high absorption takes place), it plays a vital role in the design perspective.

Attenuation is just a reciprocal of a system gain. So it is given by the ratio of signal power at the transmitting end (P_{in}) to the power at receiving end (P_{out}) of a system. Here, $P_{in}>P_{out}$



From definition, attenuation is given by,

$$A = \frac{P_{in}}{P_{out}}$$

or, $A(dB) = 10\log\left(\frac{P_{in}}{P_{out}}\right)$ ..... Equation 5-9

Attenuation is directly proportional to the frequency of the signal. That means in higher frequencies, the signal gets attenuated rapidly and vice versa. For example, there is a huge attenuation in frequency greater than 10 GHz and very little in frequency less than 10 GHz [56].

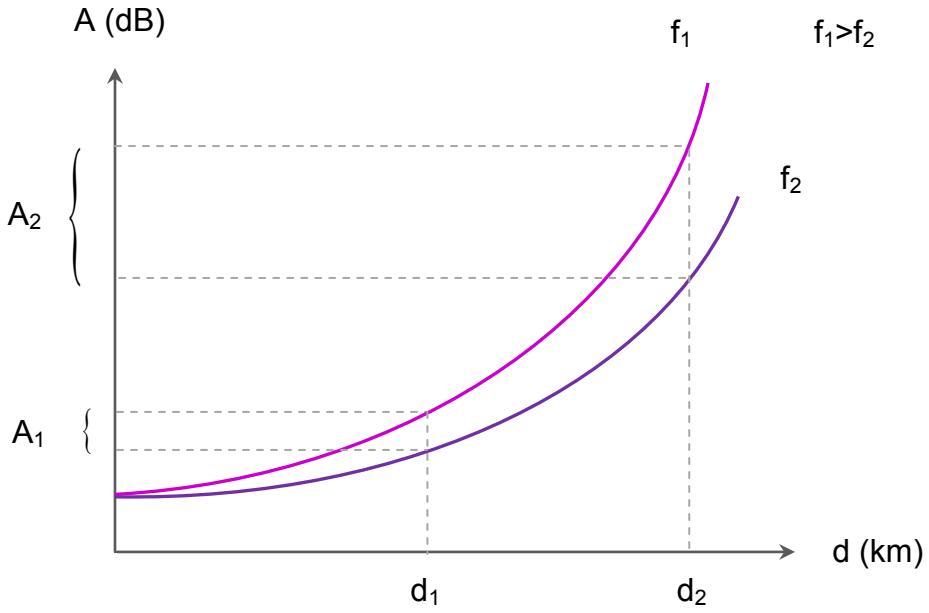


Figure 5-14 Attenuation Vs Distance

Figure 5-8 shows a graph of signal attenuation versus travelled distance for two different frequencies. From the graph, as the signals travel, signal having higher frequency f_1 (pink) gets attenuated more rapidly than does the signal having lower frequency f_2.(violet) A_1 and A_2 are the attenuation differences of the two discussed frequencies at distances d_1 and d_2 respectively. It is can also be observed that the difference in attenuation is not significant at lower distance (here, d_1) but as the distance increases, the difference is also increasing.

So it can be concluded that when the transmission distance is very near, then the selection of frequency is not that important but it becomes very important task to choose the frequency when the distance is larger. So above graph of Figure 5-8 suggest us to go for low frequency in order to get the signal less attenuated. But of course when low frequency is chosen there will be

another disadvantage for example antenna gain. So there should be a tradeoff between selection of frequency and other design parameters. We'll discuss about it later.

There are many causes of signal attenuation such as rain, fog, wind, snow, and trees. though their effects are not so noticeable most of the time. However, in higher frequencies, they become noticeable and hence contribute in additional path loss. For example, rain, fog and snow become significant sources of attenuation only when the operating frequency range lies completely inside upper bands (SHF and EHF) of microwave range. More precisely, attenuation from fog and snow become noticeable when above about 30 GHz. Rain attenuation becomes noticeable only above about 10 GHz. In one experiment, it was observed that an attenuation of about 0.02 dB/km was recorded at 2.4 GHz due to a heavy rainfall while in another experiment an attenuation of 1 dB /km was recorded at above 10 GHz. The attenuation due to rainfall is comparably very noticeable at above 10 GHz rather than at 2.4 GHz [55, 68].

Trees and forests can attenuate the signal in a significant manner if the frequency is high and the signal has to pass through the dense jungle having trees with wet leaves. In one experiment, it was seen that signal was attenuated up to the order of 0.3 dB/m at 2 GHz and 0.4 dB/m at 3 GHz. Whether the leaves are present or not or wet or dry, a single isolated tree is not usually a major problem, but a dense forest can become a huge source of attenuation [55].

Multipath Fading

When a practical scenario radio environment is considered, then we should not forget the fact that due to reflections there are a lot of radio waves (not only one wave) travelling from Tx to Rx following different paths when a signal is transmitted. Neither all the waves reach the receiver at the same time nor do they retain same phase. Multiple signals arrive at the receiver at different times and different phase. This causes either the addition or the subtraction of signal strength at the receiver depending upon their relative phases. If two signals reach the receiver at the same time with same phase, then they will add up themselves which is called constructive interference and if they reach with out of phase (phase difference of 180º) then the signal strength will be subtracted which is called destructive interference. When we have destructive interference, then the signal received at the receiver is the weakened or attenuated or the faded one and since signal was weakened due to multiple paths that the signals follow, hence signal loss due to this cause is known as multipath fading [52, 64, 69].

Diffraction Loss

The loss which occurs due to an encounter of radio wave signal with an opaque object in its path is called diffraction loss. Though the signal can diffract around the object, an inevitable loss occurs anyway. The ratio of the signal strength without obstacle to the signal strength with obstacle is referred to as diffraction loss [56].

$$L_{dif} = \frac{signal\_strength\_without\_obstacle}{signal\_strength\_with\_obstacle}$$

Diffraction loss will be more if the obstacle is round in shape. Radio signals tend to diffract better around the sharp edges [70].

Loss Due to Transmission Line between Tx/Rx and Tx/Rx Antenna

This type of loss is occurred in the transmission line or cable between the transmitting antenna and transmitter or receiving antenna and receiver. Also there may be chance of some losses in connectors. The amount of loss depends upon the type and length of cable used. Usually this type of loss is very small around 2-3 dB and can be neglected in many cases [71]. It is advised better to have cable as short as possible.

CHAPTER 6

WI-FI RADIO LINK SETUP

This chapter discusses thoroughly about the procedure of a radio link setup between the Nanostation2 of EESAT (EESAT_NS2 hereafter) and the Nanostation2 of DP_WS (DPWS_NS2 hereafter). This includes the detail procedure explaining how it has started and ended up with an establishment of a stable Wi-Fi radio link. This link was set up for the purpose of providing internet connection to the DP_WS, which is located at UNT so that the data collected by this weather station can be transferred to the CRI system web server located at Department of Computer Science, UNT via internet.

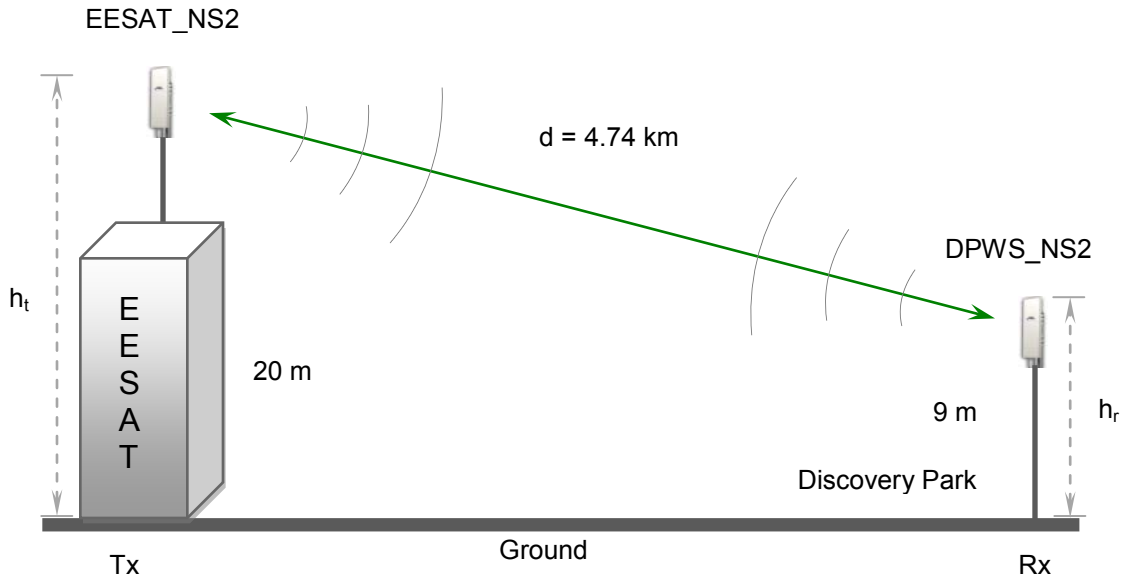


Figure 6-1 EESAT – DP_WS

6.1 Methodology

The idea is to setup a wireless connection to the already installed DP_WS. The station is collecting environmental data and storing them in the datalogger storage module. And for the data to be processed and refined, they need to be transferred from the station to the system web server. Because due to distance, it is not possible to setup a wired connection from server to the station, it is decided to go for wireless. But the station area is not facilitated with internet connection. So a wireless connection is needed which can connect the station to the internet. Thus after a field survey, the EESAT building was chosen as a source of internet. Next, a radio-link between EESAT_NS2 and DPWS_NS2 was setup using Nanostation2 from Ubiquity Networks that uses Wi-Fi technology.

6.2 Field Survey

For any communication system, prior to implement a design into real world, it is very important to do a field survey. Field survey not only helps to figure out whether the real world implementation of the proposed design is feasible or not but it also allows us modify the design making the system more robust, practical and reliable.

Talking about radio link setup between any two remotely located stations, basically the following things should be taken into account as the pre-assessment tasks before implementing the radio link design in the field:

Selection of Antenna Type

It is very important task to choose antenna type. Here, antenna type means that what radiation pattern does its signal follow, or more simply whether it is directional or omni-directional. Depending upon the type of application, antenna type is chosen to fit their design goal. For example, directional antennas are installed in either 3 or 6 sectors in cellular towers whereas omni-directional antenna is installed in every hand held unit (mobile phone set) so that it can receive signals coming from any cellular tower from any direction facilitating the unit a high degree of mobility.

In this work, because it is a point-to-point or line of sight connection, directional antennas are used in both the sites: EESAT and DP_WS. Because the goal is to link only the two mentioned sites without hampering other signals and ours also, directional antennas suit far better than omni-directional. One advantage of using directional antenna is that it radiates its power towards only one direction, which prevents the system from interfering other system and being interfered by them. Another advantage is that directional antenna has a high directivity (gain) and hence it can cover more distance than omni-directional for the same given transmitted power.

Site Selection

Another very important task is the site selection. Site selection is very important in cellular communication while installing many cellular towers in an urban area. The selection of site should be such that mobile users get signals

from everywhere and also there's a minimum (or nil if possible) of interference between their own signals and signals from other system also. Another application where site selection plays a vital role is in microwave communication while setting up a microwave radio-link. Because this type of link is LOS, one has to first take care of the visibility of the remote station from the local station and vice versa. From the name line of sight, it is clear that the two sites should be in visible range from each other. Or expressing it in simpler language, when the remote station antenna is looked at from local station antenna, the remote station tower should be visible. It should not be confused here that even if one station cannot be seen from another, a radio link may still be possible as long as they are in LOS and there's no obstacle in between which obstruct the signal completely and the transmitted power is sufficient enough to reach up to there. The tower may not be seen from another because of the fact that it may be the range limitation of human eye or unclear atmosphere. None of them prevent the electromagnetic wave to travel and reach up to the destined site.

So the basic idea is that when one running site is already there and if there's a need of another new site to be installed, then the location of the new site should be chosen in such a way that it is in LOS with the running site. The site should be chosen also in a way that it is within the transmission range (15 km for Nanostation2) of the radio equipment. In addition, one has to make sure that there is no high power line transmission pole or tower. The site should not be chosen in a place where there is a high power line nearby because it interferes

the radio signal. Also the antennas should be mounted in a tower or pole at least raising a minimum necessary height. Because the EESAT building of UNT is tall enough, LOS is clear from DP_WS and the link distance is only 4.74 km, it is chosen for all those reasons. Figure 6-2 shows a snapshot of Google map of a radio link between EESAT_NS2 and DPWS_NS2.

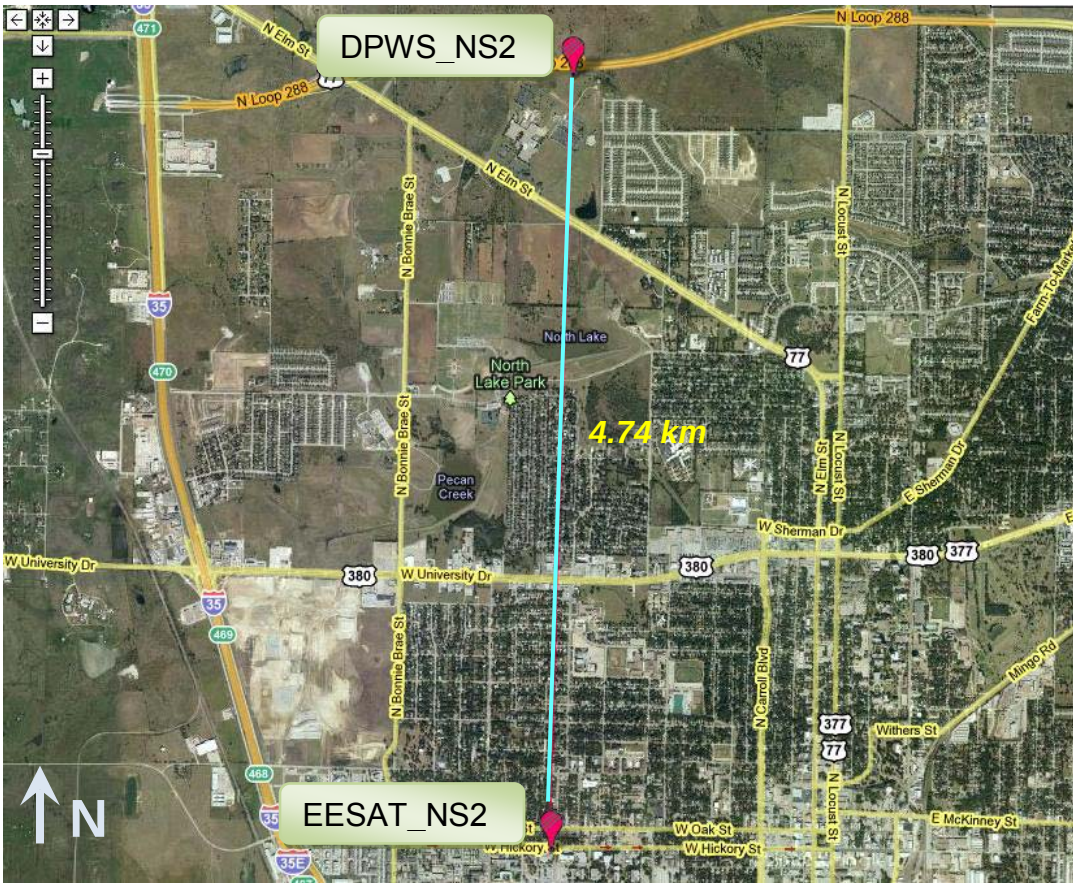


Figure 6-2 Google Map Snapshot of EESAT – DP_WS Link

Also it is important to analyze the surroundings of the installed stations and the LOS path to make sure that there is no any objects such a trees, buildings, bushes etc nearby (not exactly in the LOS path but very close to it)

which may obstruct the signal that travels in a zone called 1st Fresnel zone. There's a detail discussion about Fresnel zone later in Section 7.2.4. But for now, this section will focus on the fact that in order to get the good receive signal at the receiver, any obstacle should neither be present in LOS path nor be in the surroundings nearby either of the stations.

Recording Some Data

During field survey, it is good to have some instruments such as global positioning system (GPS), measurement tapes, binocular, compass etc. for recording some useful data such as GPS position of the towers, heights of towers, azimuth etc. that may be very helpful while designing the system.

Table 6-1 Field survey data.

FEATURE	EESAT	DP_WS
Height of antenna	25 m	9 m
Azimuth	1.4º	181.4º
Elevation	242 m	217 m
Latitude	33.214285	33.25689
Longitude	-97.151106	-97.149883
Link distance	4.74 km	
Line Of Sight	Clear	
Cable length	20 m	12 m
Tower type	Pole/Building	Pole/Ground

6.3 Technical Design

After completion of field survey, it is worth re-examining the design and making some necessary modifications according to the result obtained from the field survey if needed. Technical design is very crucial part of any project or system because overall output or performance relies on how well your system is and that rely on technical design. Once the sites are chosen, it is time to design the system accordingly. For this work, the goal was to use DP_WS. EESAT was the new site chosen accordingly after a field survey.

6.3.1 Selection of Propagation Model

It is not good decision to travel thousands of miles by car, you rather choose airplane and it is not good either to choose airplane for a very short distance journey, car might be the best choice for this. As discussed earlier in Section 5. 2.4, in order to predict out the receive power level, there are two options to select propagation model: the first one is free space propagation model and the second is two-ray propagation model. Free space model is good for short transmission distances whereas two-ray model best fits for longer distances. The selection of the model should be done accordingly.

As already discussed that the two-ray model doesn't give good prediction for shorter distances and free space model does not give good prediction for longer distances. Here's a big question: "How long distance is considered as *long* and how short is considered as *short* in this case?"

Well, to answer the above question a new term called Cross-Over distance is introduced. It is defined as the value of the transmission distance (d_c) beyond which two-ray model can be applied for better prediction. It simply determines the switch between free space and two-ray model [72]. For the value of cross-over distance, let's consider path losses of both models.

Path loss of free-space model = $FSL = \left(\frac{4\pi d}{\lambda}\right)^2$

Path loss of two-ray model = $\frac{d^4}{(h_t h_r)^2}$

Now, equating the path losses of both propagation models, we get,

$$\left(\frac{4\pi d}{\lambda}\right)^2 = \frac{d^4}{(h_t h_r)^2}$$

$$\therefore d = \frac{4\pi h_t h_r}{\lambda}$$

Now, replacing d by d_c just to give the good notation for a cross over distance, so the formula of cross-over distance is now given by,

$$d_c = \frac{4\pi h_t h_r}{\lambda} \quad \text{..... Equation 6-1}$$

where,

h_t=height of the transmitting antenna

h_r=height of the receiving antenna

λ=wavelength of the propagating signal

Now, choose the radio model for your system as stated by the two conditions given below [72]:

Condition-I: If $d < d_c$, then go for free space model

Condition-II: If $d > d_c$, then go for two-ray model

Checking for value of cross over distance for the link,

$$d_c = \frac{4\pi h_t h_r}{\lambda} = \frac{4\pi h_t h_r f}{c} = \frac{4\pi(25)(9)(2.422\times10^9)}{3.0\times10^8} = 22.83km$$

where,

h_t = height of Tx antenna (EESAT_NS2) = 25 m

h_r = height of Rx antenna (DPWS_NS2) = 9 m

f = operating frequency = 2.422 GHz = 2.422×10^9 Hz

c = velocity of light = 3.0×10^8 m/sec

From Table 6-1, we have d = 4.74 km

Comparing the two distances, we have $d < d_c$, so free-space propagation model is chosen to predict out the receive power. Equation 5-2 gives us receive power prediction formula for free space model which is

$$P_r(dBm) = P_t(dBm) + G_t(dB) + G_r(dB) - FSL(dB)$$

where,

P_t = Tx power of EESAT_NS2 = 26 dBm

G_t = Tx antenna gain of EESAT_NS2 = 10 dBi

G_r = Rx antenna gain of DPWS_NS2 = 10 dBi

FSL = Free Space Loss = path loss between EESAT and DP_WS

Adding transmission line loss in both Tx and Rx sites, total loss is then given by

$$Total\_Loss = FSL(dB) + L_{tl}(dB)$$

Eq. 5-7 gives the free space loss for free space model which is

$$FSL(dB) = 20\log(f) + 20\log(d) + 32.45$$

$$= 20\log(2.422 \times 10^3) + 20\log(4.74) + 32.45$$

$$= 113.65\ dB$$

Now putting the values of all the parameters in Equation 5-2, we get,

$$P_r(dBm) = 26 + 10 + 10 - 113.65$$

$$\therefore P_r(dBm) = -67.65\ dBm$$

In general, for radio link design, theoretically calculating formula and many other related materials can be used to predict the result of the system after implementation. But in addition to these, there are various software available which can predict the result in a quick way with higher accuracy. Using one of such software to design a model for a radio link will be discussed a little later in Section 6.3.3

6.3.2 Channel Selection

The selection of channel significantly influences the system performance. so in order to minimize interference from and to other systems, the channel should be selected very carefully when deploying a new system. As 2.4 GHz Wi-Fi technology is widely used by many of us, it's obvious that it is very crowded. There are a total of 11 channels (Ch 1-Ch 11) allowed to use in 2.4 GHz Wi-Fi in US among which only 3 non-overlapping channels are available [34].

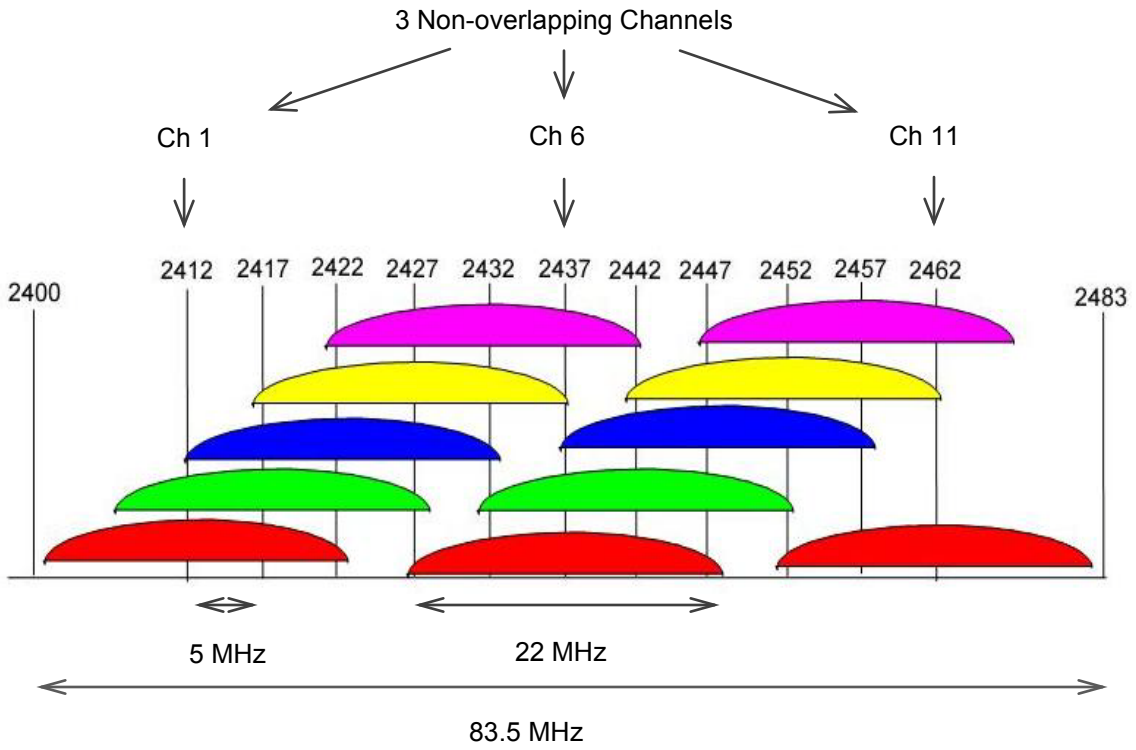


Figure 6-3 US 2.4 GHz Channel System

In US 2.4 GHz channel system, there are 11 channels spanning over a total band of 83.5 MHz ranging 2.4-2.4835 GHz. Each channel having 22 MHz of channel bandwidth is separated by 5 MHz of channel spacing. The channel allocation is as shown in Figure 6-3. Because the channels are of width 22 MHz and separated by only 5 MHz, there exists overlapping of channels with their adjacent channels. As shown in above Figure 6-3, Ch 1(leftmost red) is overlapped with its adjacent channel Ch2 (left green). Also, Ch 1 is overlapped with other channels Ch 3 (left blue), Ch 4 (left yellow) and Ch 5 (left pink). But of course, Ch 2 is the channel having highest overlapping with Ch 1. Ch 1 is not overlapped with Ch 6 and Ch 11. So they are called non-overlapping channels.

Of course, there are other non-overlapping channels such as Ch 1 and Ch 7, Ch 1 and Ch 8, Ch 1 and Ch 9, Ch 1 and Ch 10, Ch 1 and Ch 11, Ch 2 and Ch 7 and etc. These are two non-overlapping channels. Below is the table showing 11 channels and their respective overlapping and non overlapping channels [34].

Table 6-2 Overlapping and non overlapping channels.

Channel Number	Center Frequency (MHz)	Overlapping channels	Non-overlapping channel
1	2412	Ch 2, Ch 3, Ch 4, Ch 5	Ch 6 and Ch 11
2	2417	Ch 1, Ch 3, Ch 4, Ch 5, Ch 6	Ch 7
3	2422	Ch 1, Ch 2, Ch 4, Ch 5, Ch 6, Ch 7	Ch 8
4	2427	Ch 1, Ch 2, Ch 3, Ch 5, Ch 6, Ch 7, Ch 8	Ch 9
5	2432	Ch 1, Ch 2, Ch 3, Ch 4, Ch 6, Ch 7, Ch 8, Ch 9	Ch 10
6	2437	Ch 2, Ch 3, Ch 4, Ch 5, Ch 7, Ch 8, Ch 9, Ch 10	Ch 1 and Ch 11
7	2442	Ch 3, Ch 4, Ch 5, Ch 6, Ch 8, Ch 9, Ch 10, Ch 11	Ch 2
8	2447	Ch 4, Ch 5, Ch 6, Ch 7, Ch 9, Ch 10, Ch 11	Ch 3
9	2452	Ch 5, Ch 6, Ch 7, Ch 8, Ch 10, Ch 11	Ch 4
10	2457	Ch 6, Ch 7, Ch 8, Ch 9, Ch 11	Ch 5
11	2462	Ch 7, Ch 8, Ch 9, Ch 10	Ch 1 and Ch 6

Because it is always desired to have more non-overlapping channels, it is certain to go for 3 rather than 2 non-overlapping channels. However, the channels in 2.4 GHz are too much crowded and hence almost all of the channels are already occupied. In such a case, it will be necessary to go for the channel which has been least crowded. Also, it is needed to figure out the channel having less strength. So before deploying the new system in a crowded system, a radio environment should be examined thoroughly for selecting the appropriate channel. To choose the appropriate channel for the new system, a Wi-Fi spectrum analyzer called AirView2 manufactured by Ubiquiti Networks is used.

Figure 6-4 AirView2: A 2.4 GHz Wi-Fi Spectrum Analyzer

AirView2 is a cheap tiny spectrum analyzing tool for studying of all RF energy contributors in 2.4 GHz band to optimize 2.4 GHz Wi-Fi networks. It has a scan range of 2.399-2.485 GHz which covers the entire 2.4 GHz channel system completely. Its step size (interval) is 500 kHz or 3.7 frames per second (FPS). When plugged into PC, it outputs three charts: Channel usage chart, Real time chart and Waveform chart. The channel usage chart outputs the graph showing the relative crowdedness of that specific channel. Each 2.4 GHz Wi-Fi channel is represented by a bar displaying a percentage representing the relative crowdedness of that specific channel. This percentage is calculated by analyzing both the popularity and the strength of RF energy in that channel since the start of a Airview session. This chart determines the best channel to set up Wi-Fi network for optimal performance. The Real time chart outputs the graph showing real-time energy (dBm) of the 2.4 GHz signals as a function of frequency. The Waveform chart outputs the graph showing the aggregate energy (dBm) collected since the start of Airview2 session [73].

Checking of Appropriate Channel for the System

Before deploying the new system, the radio environment of both sites: EESAT and DP_WS were analyzed using AirView2. Running AirView2 in DP_WS, it is found that the channel is not much crowded. The following are the output charts obtained in DP_WS ground and EESAT terrace.

Figure 6-5 DP_WS 2.4 GHz Channel Study (Nanostation2 NOT Connected)

Figure 6-6 DP_WS 2.4 GHz Channel Study (Nanostation2 Connected)

From the output chart of above Figure 6-5 when Nanostation2 is not connected, it is seen that the 2.4 GHz channel in DP_WS is not that crowded except the channel 7. Here, there are no other channels which are interfering the channel used for the new system significantly. So channel 3 is chosen for the system. Figure 6-6 is a snapshot taken from output charts produced by AirView2 after Nanostation2 is connected.

Figure 6-7 EESAT 2.4 GHz Channel Study (Nanostation2 NOT Connected)

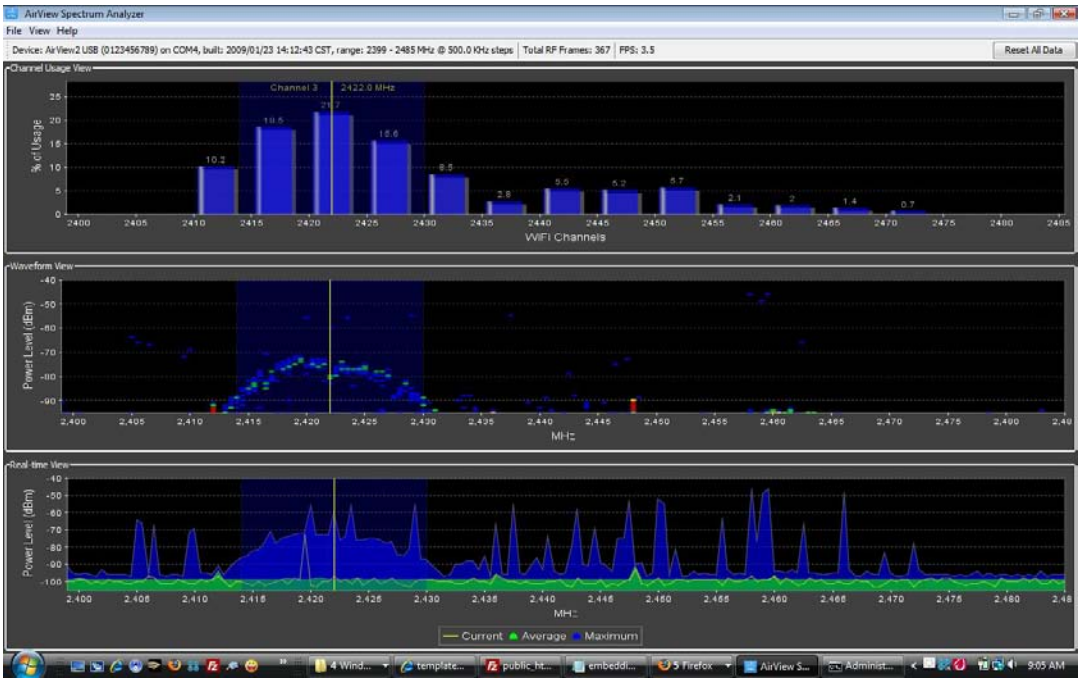


Figure 6-8 EESAT 2.4 GHz Channel Study (Nanostation2 Connected)

From the output chart of above Figure 6-7 when Nanostation2 is not connected, it is seen that the 2.4 GHz channel in DP_WS is relatively crowded than the one in DP_WS. There is no single channel left unoccupied. But it can be noticed that the Ch 3 and Ch 4 are relatively less crowded. Hence either one of them should be chosen. Since Ch 3 is selected in DP_WS, channel 3 is chosen. The Figure 6-8 is the snapshot taken from the output charts produced by AirView2 after Nanostation2 is connected.

6.3.3 Radio-Link Modeling

It is always good to design a radio-link model when deploying a new radio link system. Basically the modeling tells us about the impacts of changing different parameters on the system performance. That way, the behavior of the system can be understood in a better way and can take action accordingly before and after the system deployment whenever it is necessary.

A radio mobile software used in the system is a software used for predicting receive power [74]. With the response of the software, first of all it can be made sure if it is possible to establish the link and if the ink is possible pre-assess of the link quality can also be done. Theoretical calculation also gives the feasibility but this kind of software gives greater flexibility to check the response frequently while changing various parameters saving a lot of time.

With this software, one has to input only a few parameters such as GPS coordinates of the sites, Tx power, antenna gain, antennas heights and the operating frequency. Then it outputs important result including many important parameters such as receive signal level, path loss, link distance, azimuth, elevation angle, fade margin etc. If the result obtained is not satisfactory, the input parameters can easily be modified and see the changes in output quickly. The following is the table showing the list of input parameters that are set before simulation. The Table 6-3 shows the list of input parameters set for modeling and the Figure 6-9 shows the output result window of the simulation.

Table 6-3 Input parameters for modeling.

PARAMETER	EESAT	DPWS
Unit Name	EESAT_NS2	DPWS_NS2
LAT	33.214285	33.25689
LONG	-97.151106	-97.149883
Tx power	26 dBm	
Rx Sensitivity	-92 dBm	
Frequency range	2400-2483.5 MHz	
Antenna height	25 m	9 m
Elevation	218 m	217 m

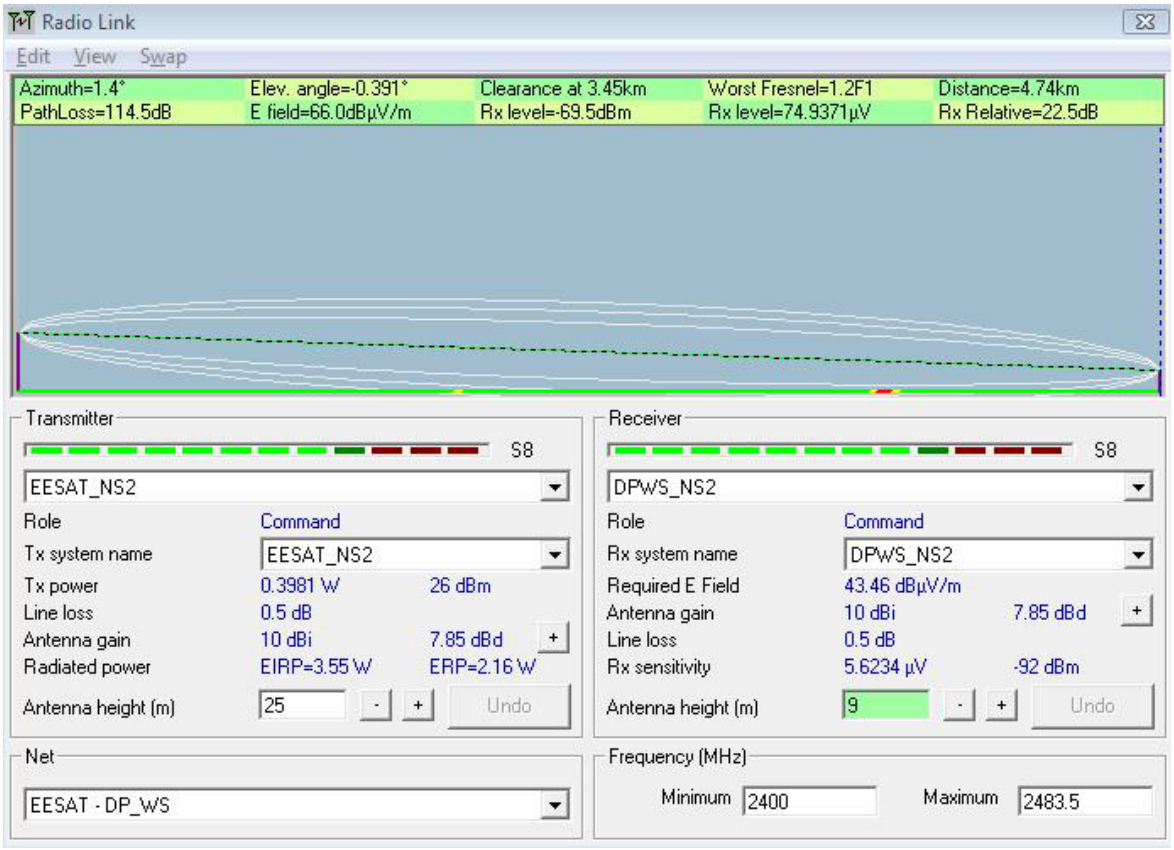


Figure 6-9 Simulation Result of EESAT - DPWS Radio-link Modeling

The parameters showing up in the faint green shaded region at the top of the simulation result window are the output parameters. Some of the important output parameters are extracted into the Table 6-4 given below for a quick view.

Table 6-4 Output parameters obtained after simulation.

PARAMETER	EESAT	DPWS
Azimuth	1.4º	181.4º
Elevation angle	-0.391	0.349
RSL	-69.5 dBm	
Path Loss	114.5 dB	
Link Distance	4.74 km	
Fade margin	22.5 dB	

6.4 Installation

Installation of Nanostation2 at DP_WS

For the installation of Nanostation2 in DP_WS, a pole of about 9 m tall was installed near (about 2 m) DP_WS. The pole is thin whose diameter is only about 2 inch. So it would be a very risky and difficult task to mount the Nanostation2 if the pole was erected vertically prior to mounting. So, a Nanostation2 was mounted at the top of the pole prior to erect it vertically. An ethernet cable (Cat 5) of length about 12 m was run from DPWS_NS2 to DP_WS. A lightning arrestor was also installed at the top of the pole and a grounding cable was run from the lightning arrestor to the grounding connection of the DP_WS. In order to make the pole sturdy, it is supported by six guy wires

in three different directions. It is very important for the pole to be sturdy or at least unaffected by strong wind. Otherwise, if the pole swings due to strong wind, then there may be a great fluctuation in RSL and the link may break down if the RSL value goes below its threshold (Rx sensitivity. Here, also compass was used to adjust the orientation of Nanostation2 and once it was adjusted then the pole was made sturdy by tightening the knots of the guy wires. The Nanostation2 at DP_WS is powered by AC power installed inside DP_WS area. A pole with the Nanostation2 mounted at DP_WS is shown in Figure 6-10 (ii).

Installation of Nanostation2 at EESAT Building

For the installation of Nanostation2 in EESAT building, a pole in the terrace which has been used for ultraviolet (UV) sensor is chosen. The pole is around 5 m tall and the height of EESAT building from ground to the base where the UV pole has been installed is about 20 m. So the total height of the antenna is about 25 m. Nanostation2 was mounted in the UV pole directing towards DPWS_NS2 using compass as shown in Figure 6-10 (i). Because DPWS_NS2 is slightly visible from EESAT building, the orientation of Nanostation2 in EESAT could easily be adjusted without using compass. However, a compass was also used for fine adjustment. Then an ethernet cable (Cat.5 unshielded twisted pair (UTP) cable) was run from EESAT_NS2 mounted on the UV pole to the router in EESAT 337 (one of the labs of EESAT building). The cable is approximately 20 m long. The Nanostation2 at EESAT is powered by an AC power at the terrace which was installed for the UV sensor.

i) EESAT_NS2

ii) DPWS_NS2

Figure 6-10 Nanostations in EESAT and DP_WS

6.5 Configuration Settings

After the installation is done, then another important task to do is configuration settings. A configuration setting is nothing but just a setting up of different parameters such as channel, Tx power, IP address etc. In many cases, a radio link failure may occur because of inappropriate or out of date (not updated) configuration settings. If a radio equipment is configured with in appropriate parameters initially prior to antenna alignment, the link may not be established successfully. And even if the link is established with those settings, there may be a chance of its breakdown later on when the unusual hostile environment such as heavy rain, thick fog etc. attacks on it.

To setup configuration settings, first a login access to Nanostations2 is needed. The default IP address of Nanostation2 set from Ubiquity Networks is 192.168.1.20. After setting the PC's IP in the same sub-domain (192.168.1.30), and entering default username and default password as ubnt and ubnt for both, we'll be directed to the "Main" page of the Nanostation2.

6.5.1 EESAT_NS2 Settings

To establish a point-to-point wireless link using Wi-Fi technology, one site has to be an access point (AP) that provides wireless connection to a wireless network and another has to be client that connects to the network. Here, in this equipment, there are two wireless modes: Access point (AP) mode and station mode. EESAT_NS2 is set as Access Point mode.

In order to minimize the interference, the rate mode is selected as Quarter (5 MHz). The output power is set to its maximum value (26 dBm). A default vertical polarization is selected. The default network settings is changed to a new static one provided by UNT computer support. Here's a new static network settings:

IP Address: 129.120.9.226

Subnet Mask: 255.255.255.240

Default Gateway: 129.120.9.225

6.5.2 DPWS_NS2 Settings

Since EESAT_NS2 is set to access point mode, DPWS_NS2 should necessarily be set to station mode. All other parameters values are set in a similar manner except the network IP Address setting. The network settings are as follows:

IP Address: 129.120.9.227

Subnet Mask: 255.255.255.240

Default Gateway: 129.120.9.225

After setting up all the parameters, the EESAT_NS2 (Extended service set identification (ESSID) of Nanostation2 of EESAT) was selected by pressing the Select button of ESSID in the Link Setup page of DPWS_NS2. ESSID is the identifying name for a wireless access point. EESAT_NS2 is an ESSID for the Nanostation2 at EESAT.

Table 6-5 Nanostaion2 configuration settings.

Site Name	EESAT	Discovery Park
Nanostation Name	EESAT_NS2	DPWS_NS2
ESSID	EESAT_NS2	
Wireless Mode	Access Point	Station
IP Address	129.120.9.226	129.120.9.227
MAC Address (LAN)	00:15:6D:AA:77:19	00:15:6D:AA:77:5A
MAC Address (WLAN)	00:15:6D:A9:77:19	00:15:6D:A9:77:5A
Network Mode	Bridge/Static	
Tx power	26 dBm	26 dBm

Rate Mode	Quarter (5 MHz)
Data Rate	13.5 Mbps
Channel	3
Frequency	2.422 GHz
Antenna Polarization	Vertical
Receive Power Level	-67 dBm
IEEE Standard	802.11g
Rate Algorithm	Conservative

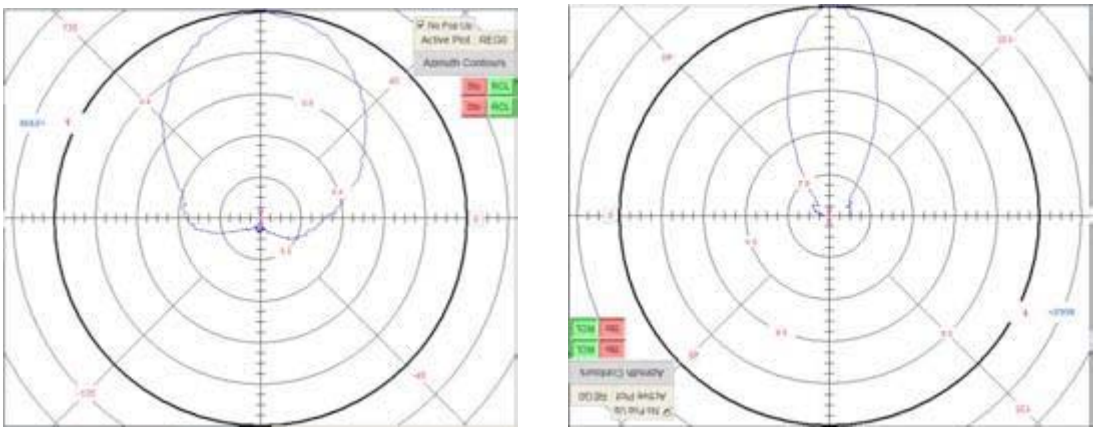
6.6 Antenna Alignment

After EESAT_NS2 (ESSID of Nanostation2 of EESAT) was selected from Link Setup page of DPWS_NS2 while operating in station mode, the link between EESAT_NS2 and DPWS_NS2 was established. Because both of the antennas were already adjusted (though not in exact direction) facing towards each other, the RSL obtained at first connection was -75 dBm.

The EESAT–DP_WS link is neither that long nor any obstacle is obstructing the LOS signal noticeably. So there is a clear line of sight for the link. Otherwise, in many cases, there may be some obstruction, or may be sites are visually unclear or link distance may be quite long. All of the above mentioned scenarios make the antenna alignment task difficult.

One very important thing to be noted and discussed here is the antenna directivity versus complexity in antenna alignment. Directivity is the ability of an antenna to focus energy in a particular direction when transmitting, or to receive energy from a particular direction when receiving. A highly directive antenna is

always sought for minimizing interference to and from other channels and for obtaining ample receive power at the receiving site. But what should also be considered is the fact that for a long point-to-point radio-link, if using highly directive antenna, it may be difficult to receive the optimum RSL while doing antenna alignment because of the highly directive nature of the antenna. The Figure 6-11 [20] below shows a radiation pattern having 60 degree of horizontal beamwidth and 30 degrees of vertical beamwidth.



i) Azimuth: 60º i) Elevation: 30º

Figure 6-11 Antenna Radiation Pattern

The Nanostation2 being used has its 3 dB horizontal beamwidth of 60 degrees and 3 dB vertical beamwidth of 30 degrees [20]. This means that the antenna of Nanostation2 can radiate its energy in 60 degree width in horizontal plane and in 30 degree width in vertical plane.

After getting -75 dBm, the Nanostation2 pole was slightly rotated and kept watching the difference in RSL value using built in antenna alignment tool of

Nanostation2. After few minutes of trying, an RSL of -66 dBm could be achieved. Knowing that the obtained RSL value was in close proximity with the theoretically calculated value (-67.65 dBm), further rotating the pole was stopped and fixed it tightly.

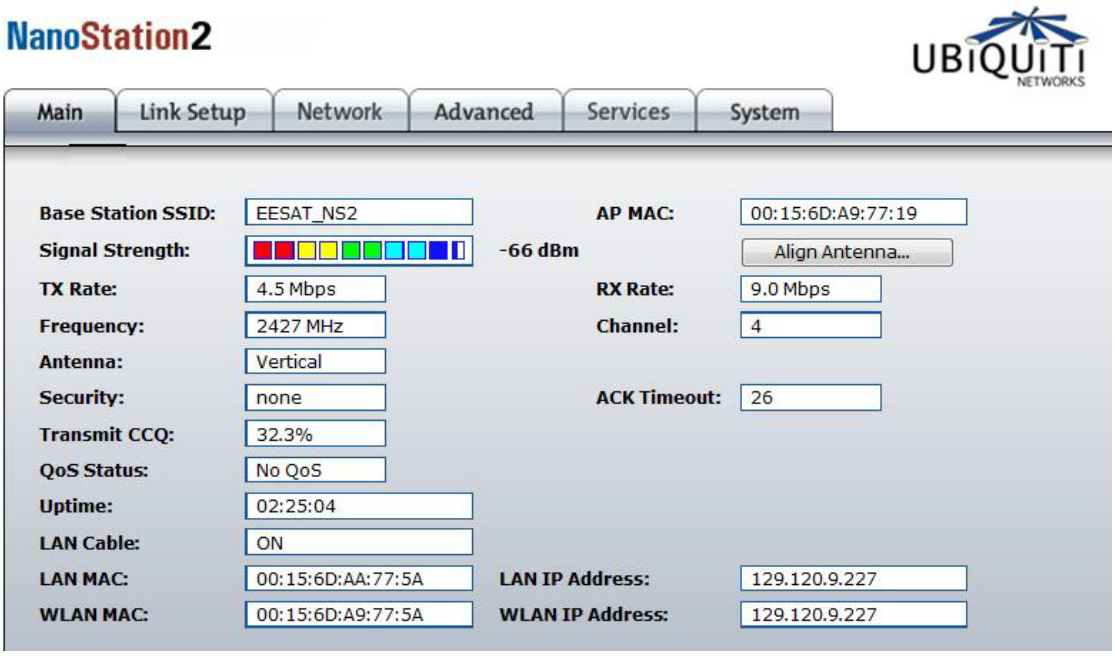


Figure 6-12 Snapshot of DPWS_NS2 Main Page

The above Figure 6-12 is the snapshot of the main page window of DPWS_NS2 after the alignment of antenna is complete.

CHAPTER 7

QUALITY OPTIMIZATION OF A WI-FI RADIO LINK

Establishing a wireless radio link is sometimes difficult because it has to sweep away all those hurdles of geographical and technical irregularities. Once the link has been established, its maintenance or the stability of the link sometimes becomes even harder due to unpredictable environmental changes. In most of the applications such as mobile communication, microwave communication etc., a radio link is supposed to transmit energy all the time. So it's very important to keep the link up all the time. For this, the system should be robust enough to counteract any probable risk of system failure. Here, system failure means the breakdown of the radio-link. A well functioning radio link may suddenly breakdown especially due to two reasons. One is due to sudden change in environmental climatic condition and another is due to strong interference from another signal. Also, poor installation of radio sites including antenna adjustments, indoor and outdoor connectors' connection etc. and some inappropriate parameters settings of radio equipment may become one of the contributors that deteriorate the link quality.

Here in this chapter, various probable causes of system quality deterioration and its impacts on the link quality are discussed. Then the chapter

focuses on optimizing the link quality by presenting the various remedies to counteract the hostile environment contributing the instability of the link.

7.1 Causes of Radio-Link Instability

Normally, RSL of an unstable link often swings in between its maximum RSL value and the threshold RSL (Rx sensitivity). This instability, at its worst condition may result in the link breakdown when received RSL value goes beyond the Rx sensitivity value. In almost all of the radio-link systems, a small fluctuation of RSL is inevitable and considered normal. Depending upon the type of radio-link, the tolerable fluctuation values may be within 0-5 dBm, 0-10 dBm, 0-16 dBm etc. as suggested by the fade margin. However, it is always desired that the RSL value to be constant. Why the link is unstable? What makes the link quality so deteriorate that often results the termination of link connection? There are several reasons which are discussed all of them here in brief.

Imperfect Antenna Alignment

Imperfect antenna alignment means that the radio antennas are not adjusted in their optimal orientations in either of or both the sites. This is one of the causes of the poor link quality often when there is a heavy rain or strong wind or any other strong environmental or technical hurdles occur. It might not be that noticeable at the time of alignment of antenna because of the normal environmental and other conditions. In many cases, antennas are fixed by tightening knots and bolts after doing few minutes or hours of alignment when

they notice that the obtained RSL is within the range between its maximum and threshold value. At that time they might think that the obtained RSL is the maximum one and hence thought that they fixed the antennas in their optimal positions. But the fact may not be as what they were thinking at that time. As a result, even if that link is up almost all the time in normal condition, it cannot counteract the worst environmental conditions such as heavy rain etc. resulting in a link breakdown or at least so much deteriorated RSL. This happened because of insufficient fade margin. Due to an imperfect alignment, the maximum RSL was not achieved and hence the fade margin was apparently reduced.

Also sometimes, the loose tightening of knots and bolts of antennas may become the cause of serious link quality deterioration and of course may also be the cause of link breakdown. Again as above, similar condition may happen when the strong wind shakes the pole or the boom and antenna which can significantly delocalize the antenna positions in both horizontal and vertical directions resulting in huge fluctuation in RSL and even link breakdown if the delocalization of antenna is significant. Similarly, the inappropriate tilting of antenna (especially microwave antenna) may result in the same scenario. Tilting of antenna is the way of adjusting antenna either in horizontal or in vertical position without affecting its position with respect to the pole or boom of tower where it is mounted or clamped. Tilting of antenna plays a vital role especially when the two radio-link sites are deployed in a significant level of height difference.

Improper Parameters Settings

One of the causes due to which the link may breakdown is setting of improper parameters in radio equipment. There are various parameters that can be set manually which may have a huge effect in the link quality. For example, if the Tx power is set to lower value for a long radio-link in order to minimize the interference where it is not that important to reduce interference, the RSL and hence the link quality degrades whenever the system encounters some hostile situations as discussed above. Also it is obvious that setting the data rate higher improves the speed of the system but at the cost of limitation on the link distance.

Interference from Other Signals

One of the most important causes of radio-link quality degradation is the interference. If a radio-link system suffers interference from any other system, then its quality goes down significantly depending upon how strong the interfering signal is. Interference may occur due to the system using same common channel and also due to from the system using the neighboring channels. The former is known as co-channel interference and the latter is known as adjacent channel interference.

Adverse Environmental Conditions

The effect of environmental factors may be noticeable in higher frequencies applications rather than in lower frequencies, but sometimes if the environmental condition is very adverse such as simultaneous heavy rain and

strong wind, then some lower frequencies may also get affected. Other environmental factors like snow, fog etc. also contributes to the link quality degradation. The radio signal gets highly attenuated in all of these environmental adverse conditions and hence the RSL decreases.

Inappropriate Antenna Polarization Settings

This cause is also one of the causes due to improper parameters settings which have just been discussed a little earlier. I think it is worth discussing this parameter separately in a little detail, because it is also one of the very important parameters that needs to be carefully selected while configuring radio equipment. Polarization of antenna is how the radio wave travels from Tx to Rx. For the Rx to receive the signal transmitted by Tx, it should have the same antenna polarization as Tx has. So the polarization is set same for both the sites. But there exists some cases when another system located nearby interferes the present system because of the same polarization. So this may result in interference which in turns results in the degradation of the link quality.

Disrupted Fresnel Zone

In many LOS radio link applications, Fresnel zone plays a very important role especially when the transmission distance is longer. In this type of radio link, a line of sight doesn't only mean that there is only one clear line of sight path between Tx and Rx, but there exists an ellipsoidal region called Fresnel zone around the LOS path which should also be clear of any obstacles. If any

obstacles do exist in the region between Tx and Rx even if it is not in the direct LOS path, the RSL may be degraded in a significant amount. The Fresnel zone effect is due to an insufficient raised height of transmitting and/or receiving antennas. The Figure 7-1 [75] shows the picture of Fresnel zone being disrupted even when the line of sight path is clear. The trees lying within the Fresnel zone are being obstacles for the radio link given in the picture.

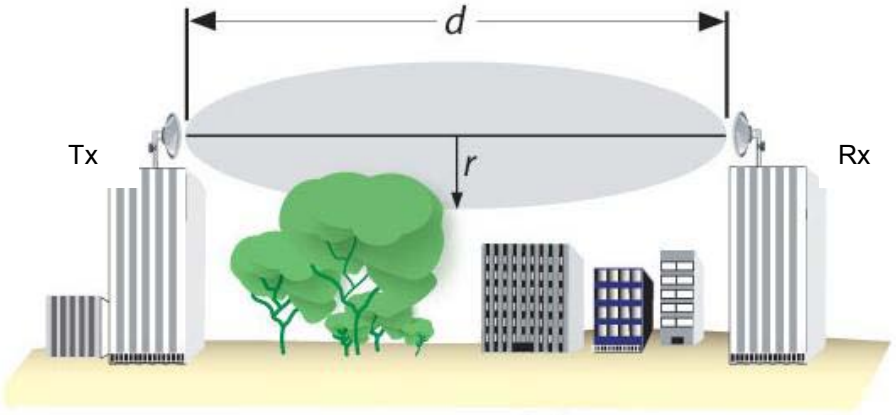


Figure 7-1 Disrupted Fresnel Zone

7.2 Remedies of Radio-Link Instability

As discussed above in Section 7.1, the instability of a radio link may result in its breakdown at the worst condition. For a radio-link to be robust enough to encounter any unfavorable conditions and counteract accordingly, it should be very well designed. A well designed radio link is capable of facing any probable unpleasant circumstances and continues functioning well even in that kind of adverse surroundings. A robust design of a radio link includes both a detail excellent field survey and a powerful technical design. A properly prepared design includes adjustment of antennas perfectly, setting of all the parameters

values properly, keeping ample fade margin, especially design to counteract the effect of interference, choosing various diversity techniques to counteract the effect of multipath fading etc.

7.2.1 Adjustment of Antennas Perfectly

As discussed a little earlier in Section 7.1 about how the improperly adjusted antennas can result the radio link instability and even the link breakdown. So it is very important to do the antenna alignment as perfectly as it could be done. Antenna adjustment includes basically three things: adjustment of antenna with respect to pole or boom of tower, tilting of antenna and properly tightening of knots and bolts of antenna clamps or the screws used in tilting.

Adjustment of Antenna Position Relative to Pole

This is simply to fix the antenna position on the pole which is called antenna mounting. This is very important when the link distance is long because a small disorientation of Tx antenna can result in targeting Rx antenna in a wrong direction in a great deal. This is depicted in a Figure 7-2 below.

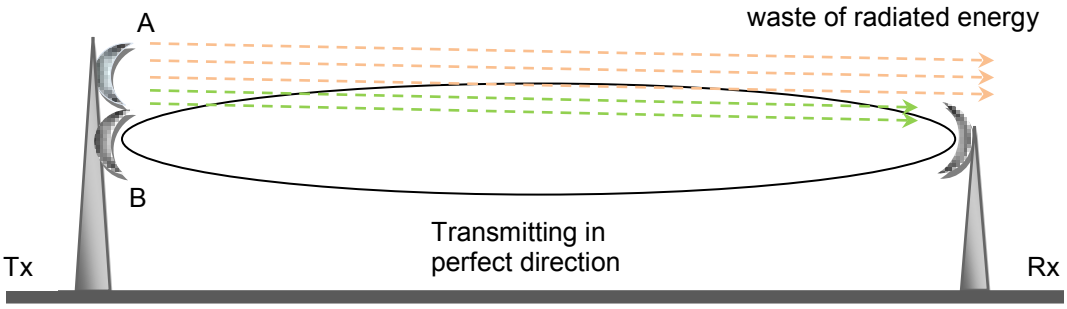


Figure 7-2 Waste of Energy Due to Improper Antenna Adjustment

In above Figure 7-2, it is noticed that only a few portion of energy (denoted by dotted green line) is captured by Rx antenna when antenna is fixed in position A. In this case, some part of energy (denoted by dotted orange line) is wasted due to the improper alignment of antenna A. But when the antenna is fixed in position B, then almost all of the energy radiated is captured by the Rx antenna.

Tilting of Antenna

In radio link where the two sites are in different height levels, there is a need of tilting of antenna. It's sometimes necessary to tilt the antenna especially when one site is at much higher or lower altitude relative to the other. In such a situation, one cannot establish a radio link without tilting of antenna. So tilting should be done in such a way that the receiving antenna gets almost all of the radiated energy. There are two types of tilting: vertical and horizontal tilting. Mostly vertical tilting is widely used in most of the radio link system.

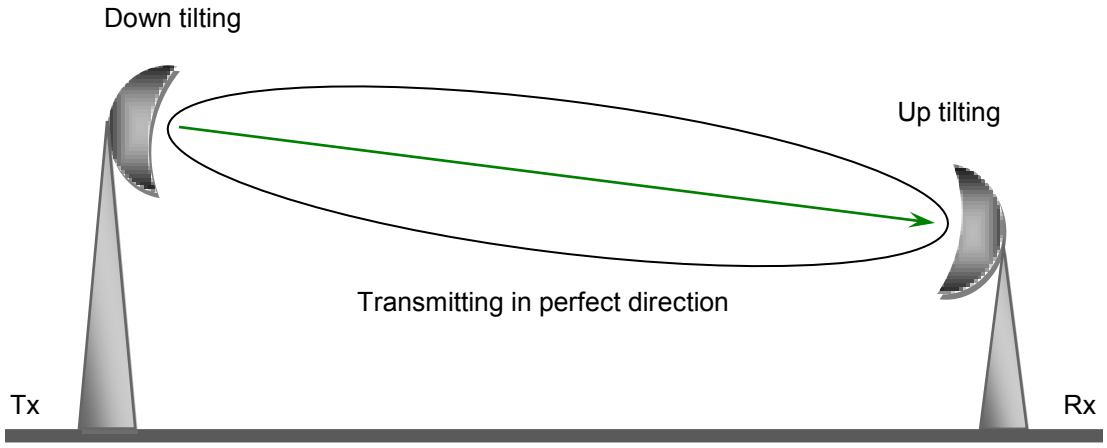


Figure 7-3 Vertical Tilting of Antenna

Tightening of Knots and Bolts

Another simple but important task in adjusting antenna is tightening of knots and bolts in antenna clamps while mounting. It is also important to check for the knots and bolts or screws used for antenna tilting. If they are left not tightened after antenna alignment, the strong wind can change their orientation and propagation direction may be changed which contribute in deteriorate the RSL. So after final adjustments of both the antennas, it's always good idea to check for all the knots and bolts and screws to ensure that the antennas are tightened well. If it is done properly, then even if there is strong wind, it won't affect the antenna position that much.

Both the Nanostaion2 are adjusted in EESAT and DP_WS with the help of compass. And after obtaining an RSL of -68 dBm that matched with that of design value (-67.72 dBm), the antennas are fixed and tightened properly.

7.2.2 Appropriate Settings of Various Parameters

Improper settings of parameters also can result in the system performance degradation in a great deal. That's why it is very important to put the values of all the parameters properly while configuring the radio equipment. Here in this section we'll discuss about selection of Rate Mode (spectral width), Data Rate, channel, setting of Tx power, antenna polarization setting, selection of IEEE802.11 mode etc.

Selection of Data Rate

Data rate determines at what speed the system can transfer data. It is obvious that everyone wants a higher data rate. But it can't be simply set as higher as we want because of other detrimental effects associated with that. Data rate is inversely proportional to the RSL and hence the link distance as well. In some cases, if the data rate is set higher in order to have a greater speed, then the link connection may be lost due to significant decrease of RSL which results the RSL go below the threshold value. Also when data rate is increased, the receiver sensitivity decreases. So there should always be tradeoff between data rate and RSL as well as between data rate and Rx sensitivity.

For example, the available data rates along with their corresponding Rx sensitivities are shown in Table 3-15 is shown in the Figure 7-4 below.

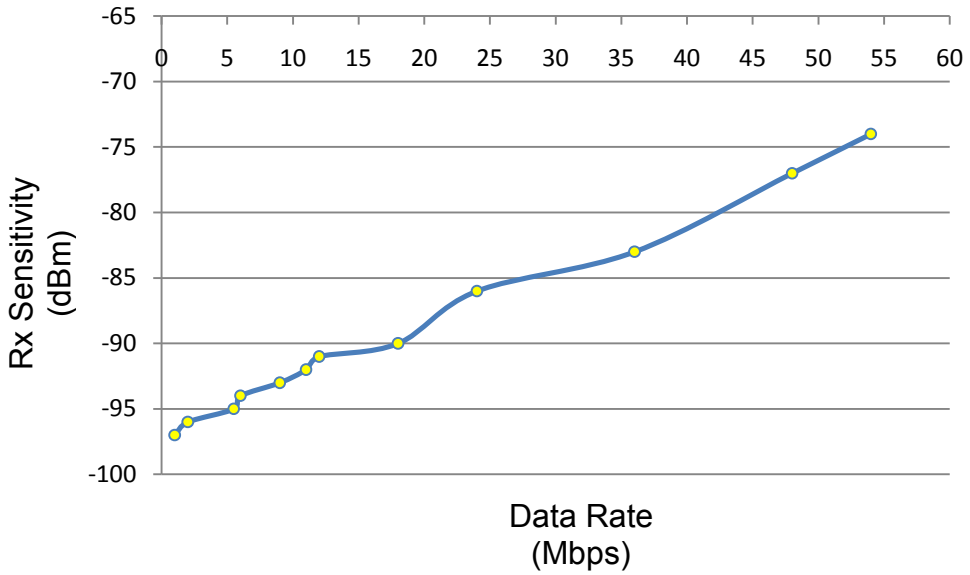


Figure 7-4 Data Rate Vs Rx Sensitivity from Table 3-15

The graph of above Figure 7-4 tells us that when the data rate is set higher, then the Rx sensitivity decreases and vice versa. But having higher data rate is always desired and at the same time Rx sensitivity is also desired to be higher as well. But both can't be achieved at the same time because they are mutually exclusive. With higher Rx sensitivity, the link distance can be extended and hence a good fade margin level can be designed. Also higher data rate means higher speed of data transmission. So it's very important to choose the data rate according to the need of this application. When there's a need of higher data rate rather than the transmission distance, then one can go for higher data rate and vice versa. For example, it a short (let's say 2 km) link is to be established for video conference, the data rate could be much higher priority rather than Rx sensitivity.

When the data rate is increased, the RSL value decreases accordingly. Again, there should be tradeoff between data rate and RSL. In this work, a data rate of 13.5 Mbps is selected with a receiver sensitivity of -92 dBm in Quarter rate mode (5 MHz).

Selection of Rate Mode (Spectral Width)

Rate mode is also one of the important parameters to be considered. Here, in the current system rate mode is just the selection of spectral width. There are 3 options for the system (in Nanostation2) which are: Quarter rate mode having 5 MHz spectral width, half rate mode having 10 MHz spectral width and full rate mode having 20 MHz spectral width [21].

Selecting narrower spectral width increases the number of non-overlapping channels which reduces the interference. Also this increases the power spectral density (PSD) of the channel and enables the link distance to be increased. But a major drawback in reducing the spectral width is that it reduces the throughput of the system [21]. So again, selection of rate mode should also be carefully done. In this system quarter rate mode is selected in order to decrease the potential interference.

Selection of Channel

Selection of channel may be one of the most important tasks especially when the channel to be used is already crowded by other applications (2.4 GHz application here). When deploying the system, one should carefully select the channel so that there's as less interference as possible from and to other running systems. Significant amount of interference can degrade the performance of both the interferer and the system being interfered.

In order to explain how wisely the channel can be selected when deploying a new system, a picture of North American channel system for 2.4 GHz is shown below in Figure 7-5 [34]. The US system only allows 11 channels though other extra two channels are also allowed in Europe and one additional on top of that in Japan. The 2.4 GHz channel system operating range is 2.4 – 2.4835 GHz spanning over the total band of 83.5 MHz [29, 32].

3 Non-overlapping Channels

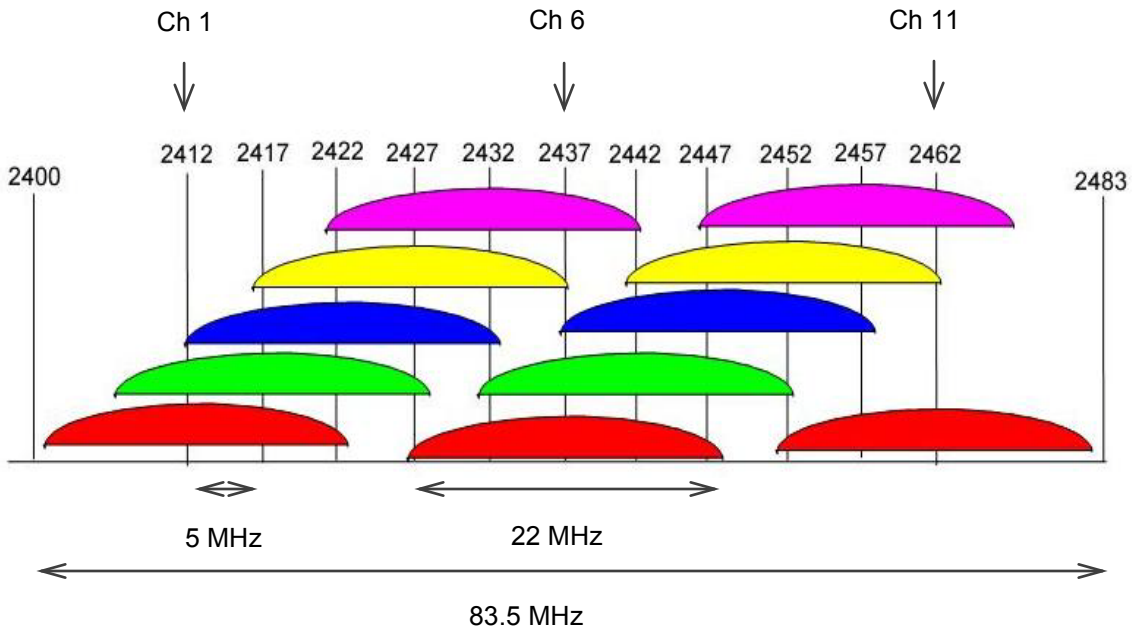


Figure 7-5 A 2.4 GHz North American Channel System

There are 11 channels (Ch 1-Ch 11) one of each separated by 5 MHz from its adjacent channel. The channel bandwidth is 22 MHz. Among 11 channels, there are only 3 non overlapping channels as shown in the above figure shaded by red color [34]. They are Ch 1, Ch 6 and Ch 11. These channels do not overlap at all with each other. So, if a system is to be deployed in the radio environment where any two of the three non overlapping channels are occupied, then the new system can use the third unused channel hence it won't interfere the other two channels. Or truly speaking, it will have only a very little interference which should be within tolerable region for all the system.

However, the channels in 2.4 GHz are too much crowded and hence almost all of the channels are already occupied by at least one system. In this case, there's no question of non-overlapping channel. So the channel which has been least crowded should be chosen. It will be even better if the channel having less strength could also be identified. These can be achieved by using spectrum analyzer.

Using AirView2 as discussed in Section 6.3.2, the best channel for the system is identified as Ch 3 (2422 MHz) since this is relatively less crowded with less signal strengths.

IEEE 802.11 Mode Selection

There are already a lot of Wi-Fi devices available in today's market which are compatible for many IEEE standards. For example the device that is easily found in today's market is compatible for 802.11g and also compatible for 802.11b networks. This is good for interoperability but not always especially for those applications where 802.11b is not needed and want to exclude it from the network in order to avoid unnecessary interference and hence to achieve better throughput of the system. So 802.11g is selected as 802.11 IEEE mode in the present system.

Tx Power Settings

As the RSL is directly proportional to Tx power, it is always good to transmit at higher power to make the link robust but staying within the limitation

fixed by the country regulation. In the link EESAT_NS2 to DPWS_NS2, since the link is 4.74 km (not very near) and the radiation is directional also, the signal is transmitted at its highest power, i.e., at 26 dBm. Higher Tx power is always desired because of the fact that higher transmitted power yields a greater throughput. Because the beam radiated is directional and at a significant height, it doesn't interfere other signal that much.

Rate Algorithm Settings

Appropriate selection of Rate algorithm allows clients to drop to lower connection rates (data rates) as signal quality or RSL drops to maintain the stability of the link. In Nanostation2, there are three options for choosing rate algorithm: Optimistic, Conservative and EWMA. Among the three, Conservative rate algorithm is selected because it allows to automatically switch between higher and lower data rates depending upon the link quality condition and hence maintaining the stability of the link almost all the time [21].

Antenna Polarization Settings

As discussed above, the Rx antenna should have the same antenna polarization as Tx. But there may be some cases when there is another system nearby having same antenna polarization and antenna facing to either Tx or Rx antenna of another this system. So this may result in interference which in turns results in the degradation of the link quality. If such a case is encountered, then

the polarization of the system can be changed. That way, the system can be prevented from being interfered by other system or interfering other system.

7.2.3 Use of Various Diversity Techniques

Radio link communication reliability for a given Tx power in a multipath environment can be increased through diversity techniques. Diversity technique is a method for improving the reliability of a radio signal by using two or more communication channels with different characteristics. These techniques play a vital role in combating against fading in multipath fading and co-channel interference. The idea behind diversity techniques is that if signals are received over multiple, independent channels, the largest signal (signal having highest power) can be selected for use. We'll discuss here the most important three diversity techniques though there are few more of them [76].

Space Diversity

This technique (also called as antenna diversity) talks about using multiple transmitting antennas and/or multiple receiving antennas having same frequency channel and using the strongest received signal among other signals received at the receiver with various different signal strengths. Thus this scheme improves the quality and reliability of a wireless link. Each receiving antenna experiences a different interference environment. Thus if one antenna is experiencing fading very badly, it is often likely that another antenna may be receiving a better signal [77]. That way, the receiving antenna always get chance to receive the signal

having stronger strength and hence maintaining reliable connection. This is illustrated with the help of the Figure 7-5 given below:

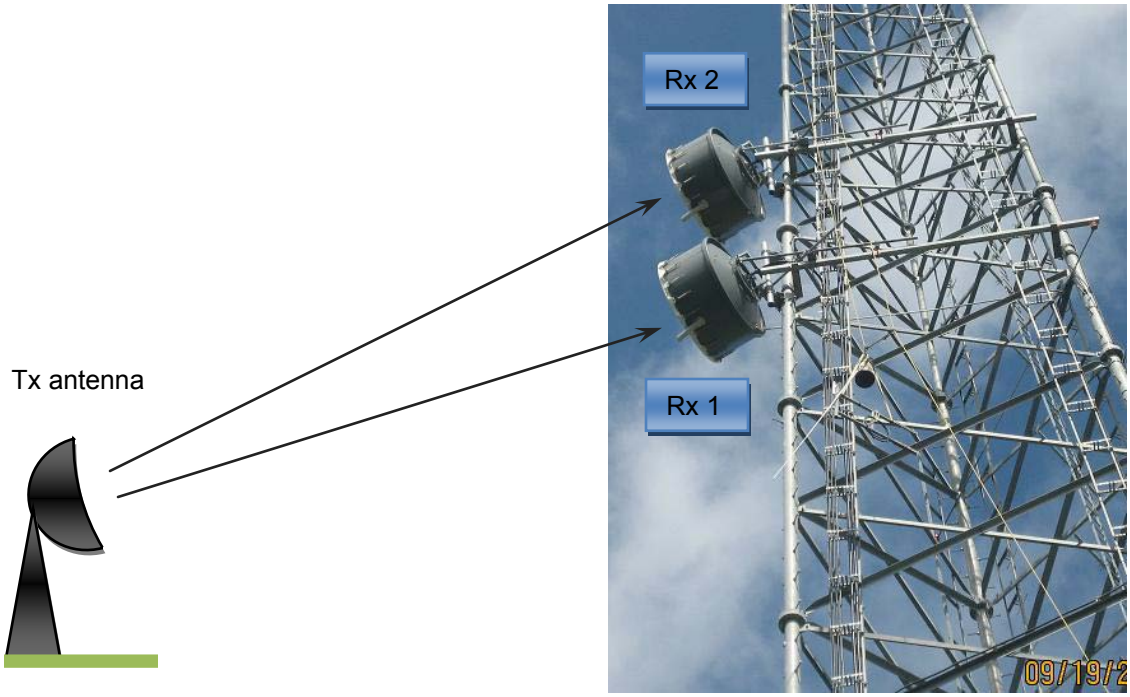


Figure 7-6 Space Diversity Using Two Antennas in Receiver

Let's take an example of two antennas used in receiver site separated by one wavelength of the frequency used as shown in above figure. When the Tx antenna transmits, then its signal reach at the receiver antennas Rx 1 and Rx 2 at different signal strengths. Sometimes, Rx 1 has the strongest signal and sometimes Rx 2 and other times signals at both receivers are around the same level. At all cases, the strongest signal is chosen. In this way effects of fading can be minimized using two physically separated antennas. The reliability can be even more increased by increasing the number of antennas. Multiple radio

system is not implemented in this work since there's no significant multipath fading in this case.

Frequency Diversity

The use of multiple frequency channels to transmit a signal and choosing the strongest received signal among many other signal received at the receiver side is known as frequency diversity. For the same position of Tx and Rx antennas, the different channels receive signal at different strengths at different times. But it selects the signal having highest strength every time thus increasing the average signal-to-noise ratio (SNR). The minimum channel difference depends on the path difference. Larger the path difference, the smaller the required difference in frequency channel.

Polarization Diversity

The use of two different antennas of different polarization (i.e., horizontal and vertical) for capturing the received signal having the highest strength to provide diversity reception is known as polarization diversity. The antennas take advantage of multipath propagation characteristics to receive separate uncorrelated signals [56].

Due to reflections, the original polarization of the transmitted signal may get altered, so this characteristic of a signal can be used to create two separate signal channels. Thus, cross-polarized antennas can be used at the receiving site only. Since the orientation of the antenna is not rigidly defined in a portable

handheld unit such as mobile phone set, the diversity technique is particularly advantageous in this kind of unit. This type of technique doesn't allow to use more than two channels. This technique offers relatively low performance than the other above mentioned two techniques [64, 78].

7.2.4 Mounting of Antennas at Sufficient Heights

As already discussed in Section 7.1, due to an uncleared Fresnel zone, the signal may get degraded in a significant amount even there's a clear visual line of sight between Tx and Rx. To better understand this, let me introduce the term Fresnel zone.

Fresnel Zone

Fresnel zone is the area around the visual line of sight that radio waves spread out into after they leave the antenna forming a long ellipsoid that stretches between the two (Tx and Rx) antennas. Receive signal strength and hence system performance not only depends on LOS signal alone but is also affected by the obstacles lying within the 1st Fresnel zone. If there's an obstacle near the LOS path, reflections from the obstacle may cause the reduction of power received at the receiver. In order to avoid such obstacles and their detrimental effect on RSL, a minimum of 60 % of 1st Fresnel zone should be cleared. Such a cleared path can be treated as a clear free space path [56, 79].

The 1st Fresnel zone is such that the difference between the direct path and an indirect path that touches a single point on the border of the Fresnel zone is half the wavelength as shown in Figure 7-6 below [80].

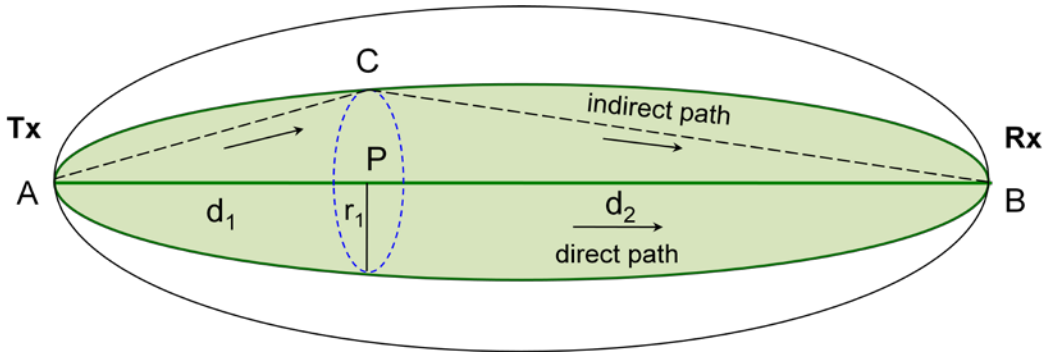


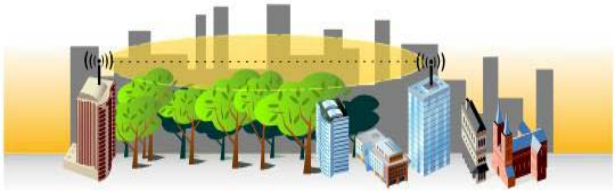
Figure 7-7 1st Fresnel Zone

In the above figure, AB is the direct path and ACB is indirect path that touches a single point C on the border of the Fresnel zone. So, according to the definition of 1st Fresnel zone, in order the green shaded region to be 1st Fresnel zone, we should have,

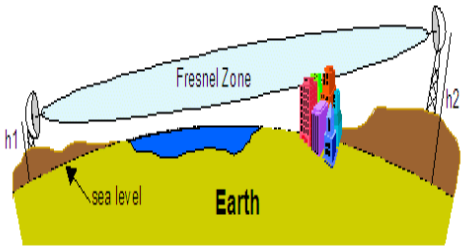
$$ACB - AB = \frac{\lambda}{2}$$

Let's consider any point P on direct path AB, then the blue dotted circular section of radius r_1 is the 1st Fresnel zone at point P. The cross section of the 1st Fresnel zone is circular. Subsequent Fresnel zones are annular in cross section, and concentric with the first [79].

The following are the two pictures shown below in Figure 7-8 [80-81] showing how the Fresnel zone can be disrupted even when there's a clear direct path between Tx and Rx antennas. Also, even when there's nothing for obstructing the signal in between Tx and Rx, there's still a chance of Fresnel zone being disrupted due to earth's surface and insufficient antenna heights.



(i)



(ii)

Figure 7-8 Fresnel Zone being Obstructed in Various Ways

In both of the pictures of Figure 7-7, the exact direct paths are clear. But the Fresnel zones are not clear in either case. They are somewhat blocked by trees in first and by buildings in latter pictures. In either cases, the signal will get obstructed some amount and hence RSL will be decreased. The reason behind the zone being uncleared is insufficient antenna heights. So a good design tells us to raise the antenna heights up to that point where we'll have at least 60% of 1st Fresnel zone cleared.

Calculation for the Radii of 1st Fresnel Zone at Different Locations

Here, let's calculate the radii of 1st Fresnel zone at different points in between EESAT_NS2 and DPWS_NS2. For this a formula for the radius of the

zone is needed. Referring to the Figure 7-7, the radius of Fresnel zone is given by the following equation [79],

$$r_n = F_n = \sqrt{\frac{n\lambda d_1 d_2}{d_1 + d_2}} \quad \text{..... Equation 7-1}$$

where,

$r_n = F_n$ = The n^{th} Fresnel Zone radius (m)

d_1 = distance of P from one end (m)

d_2 = distance of P from the other end (m)

λ = wavelength of the transmitted signal in (m)

For n=1 (1st Fresnel zone), Eq. 7-1 becomes

$$r_1 = F_1 = \sqrt{\frac{\lambda d_1 d_2}{d_1 + d_2}} \quad \text{..... Equation 7-2}$$

The cross section radius of the 1st Fresnel zone is maximum in the center of direct path AB. Let's P be at the center of the pat AB, then $d_1=d_2$. There is a simplified version of above formula for calculating the radius of the 1st Fresnel zone in the center of direct path given by

$$r_{1c} = F_{1c} = 17.32\sqrt{\frac{D}{4f}} \quad \text{..... Equation 7-3}$$

where,

D = link distance (km)

f = frequency of the transmitted signal (GHz)

i) Calculation Near EESAT_NS2

The equation Eq. 7-2 gives the formula for the radius of 1st Fresnel zone at distance d_1 from the Tx. Here EESAT_NS2 is Tx. The nearest possible obstacle that may lie within in the 1st Fresnel zone is at 5 m from the antenna.

We have,

d_1=5 m, d_1+d_2 = 4.74 km and d_2 = 4.735 km

f = 2.422 GHz

$$r_1 = F_1 = \sqrt{\frac{3\times10^8 \times 5 \times 4735}{2.422\times10^9 \times 4.74\times10^3}} = 0.7867\, m = 2.6 \;\; ft.$$

Now, 60 % of 2.6 ft = 1.56 ft

Conclusion:

From the field survey at EESAT_NS2 site, it is clearly seen that 1.56 ft below the direct path is free of any obstacle. So the 1st Fresnel zone at that point is clear.

ii) Calculation Near DPWS_NS2

The nearest possible obstacle that may lie within in the 1st Fresnel zone is at 300 m from the antenna. There's a tree of about 5 m height.

So, we have,

d_1=300 m, d_1+d_2 = 4.74 km and d_2 = 4.44 km

f = 2.422 GHz

$$r_1 = F_1 = \sqrt{\frac{3\times10^8 \times 300 \times 4440}{2.422\times10^9 \times 4.74\times10^3}} = 5.9\, m = 19.47 \;\; ft$$

Now, 60 % of 5.9 m = 3.54 m

Conclusion:

From the field survey at DPWS_NS2 site, it is observed that the height of LOS path from the ground at this point (300 m from DPWS_NS2) is at least 10 m and subtracting the 60% of 1st Fresnel zone radius (3.537 m) from this height, the result is 6.463 m which is still higher than the tallest tree (obstacle) of height 5 m at this point. So the 60% of 1st Fresnel zone is clear.

iii) Calculation at the Center of EESAT_NS2 and DPWS_NS2

Checking if the obstacle lies within in the 1st Fresnel zone at the center of EESAT_NS2 and DPWS_NS2, then Eq. 7-3 gives the radius for 1st Fresnel zone at the center of the link,

We have,

D = 4.74 km

f = 2.422 GHz

$$r_{1c} = F_{1c} = 17.32\sqrt{\frac{D}{4f}}$$

$$r_1 = F_1 = 17.32\sqrt{\frac{4.74}{4\times 2.422}} = 12.12\ m = 39.99\ ft$$

Now, 60 % of 39.99 ft = 23.99 ft

Conclusion:

From the field survey at the halfway in between the sites EESAT_NS2 and DPWS_NS2, it is seen that 23.99 ft below the direct path is free of any obstacle. So the 1st Fresnel zone at that point is clear.

So, the initially designed heights of Nanostations (9 m and 25 m in DP_WS and EESAT) in both sites are ample enough to counteract the effect of the Fresnel zone.

7.2.5 Design of Ample Fade Margin

Fade margin is the amount by which an RSL can be reduced without causing system performance to fall below a specified threshold value. It is extremely important to keep at least some amount of fade margin in every radio link systems in order to counteract the probable fading. To illustrate how important role does the fade margin play in a radio link system, here's one example.

Let's take a hypothetical example of an 18 GHz radio link established between two stations located at a distance of 16 km (say) from each other. Its current RSL is -50 dBm and Rx sensitivity is set to -65 dBm at 5 Mbps. The link works well under normal environmental conditions. But when there's a heavy rainfall due to which signal attenuates by 1 dB/km, then the attenuation in traversing 16 km link will be 16 dB and hence the RSL value decreases to -66 dBm which is below the preset receiver sensitivity (-65 dBm). In this condition, the radio-link will breakdown.

The above example clarifies that the insufficient fade margin may not work at all when there is an abnormal condition as illustrated in above example even if the radio link works very well in normal condition. For the above example, to be in safe side, the Rx sensitivity should be set higher (let's say about -75 dBm at 3 Mbps). That way, even if the heavy rainfall occurs, the RSL value still lies above the Rx sensitivity and the link remains connected. Also if the obtained RSL of -50 dBm was not the maximum value as suggested by design, one should try to attain that value and that way the system will have large fade margin.

For the present system,

Rx sensitivity = -92 dBm @ 13.5 Mbps

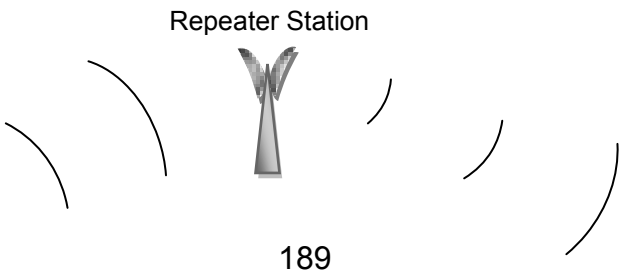
RSL = -68.0 dBm

Therefore, fade margin = |(-92)-(-68)| = 24 dBm

7.2.6 Use of Repeaters

A repeater is an electronic device used for the extension of radio-link. Repeaters are generally of two types. First one known as passive repeater is used for rerouting the transmitted signal towards the receiver when LOS path is obstructed and the another which is used to extend the link distance by retransmitting the signal at a higher power level is known as active repeater [82].

Use of a repeater for rerouting a LOS blocked signal



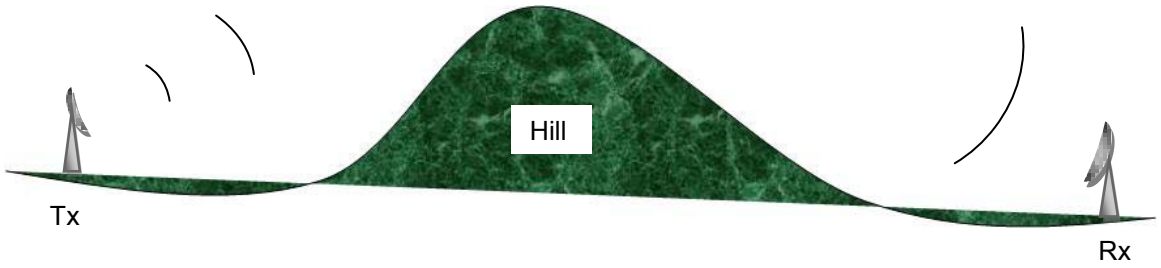


Figure 7-9 Use of a Passive Repeater for Rerouting a LOS Blocked Signal

Even if the link distance is not far, the transmitted signal may be blocked by a huge obstacle as shown in above Figure 7-9 lying in between transmitter and receiver such as a giant hill, a huge tall building etc. A repeater station is used in such case. Since transmitter and receiver both are in LOS with the repeater as shown in figure, it is linked with both of them and hence can forward the transmitted signal from the transmitter to the receiver acting as a relay.

Use of Repeater to Extend the Link Distance by Enhancing the Power

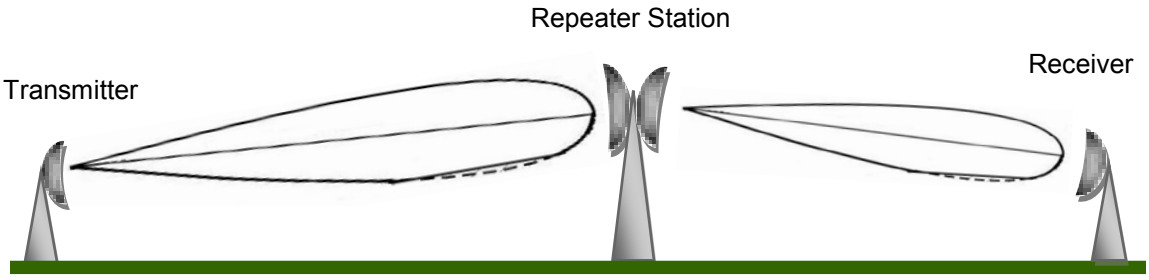


Figure 7-10 Use of an Active Repeater to Retransmit the Weakened Signal

Sometimes, it really becomes important to establish a long distance radio link between two stations separated by several hundreds of miles with each

other. In such a case, a powerful radio device with high gain antenna is needed that can transmit its signal to cover such a long distance. But it is really a hard job to establish such a long distance radio link. If anyway the link is established there will be a very poor receive signal level and a radio-link having such a poor RSL is reliable at all. That type of radio-link may frequently breakdown even for a small change in environment. So, it is better to install one station in between the transmitter and the receiver (depicted in above Figure 7-10) where it can intake the transmitted signal and retransmit it at a higher level power after amplification. That type of station bridging between the Tx and Rx is called active repeater. That way, a sufficient amount of RSL can be received at the receiving site enhancing the link reliability.

CHAPTER 8

THROUGHPUT PERFORMANCE MEASUREMENT

The chapter begins with first introducing the term "throughput" and then some of the analogies and differences between the two closely related terms "bandwidth" and "throughput" are discussed. It also discusses in brief about why it is worth studying and analyzing the throughput.

Then various types of throughput experiments carried out by changing different parameters are discussed. Then the gist of this chapter, throughput measurement of EESAT_NS2 – DPWS_NS2 link and the analysis of its results are also discussed. Also discussed is the various factors affecting the throughput performance of a wireless link. In addition, the comparison of the throughputs of different IEEE Standards are reviewed. This chapter also discusses about the various ways to maximize the system throughput. It introduces the throughput measuring software called Iperf. Finally, this chapter discusses on the throughput results of the system.

Throughput

Throughput is the average rate of successful message delivery over a communication channel; or in other words, it is the amount of data transferred successfully over a link from one end to another in a given period. It is usually expressed in bits per second (bps) or kilo-bits per second (kbps) [83].

$$Throughput = \frac{total\ file\ size\ (bits)}{time\ taken\ for\ transferring\ (\mathrm{sec}onds)}$$

Throughput is a key measure of a network (LAN or WLAN) performance. Here in this application, it is a radio-link quality measuring parameter. It is different than the RSL quality of the link. Though the RSL value is very good, throughout may not be because of interference from other devices using same channel. Though the manufacturers qualify their products' performance by the data rates, this parameter alone does not define the system performance, but it's the throughput that does so. For example, though it is rated 100 Mbps of data rate in Cat5 LAN cable, its actual speed is only around 93 Mbps which can be called as its throughput. Also, the maximum theoretical data rate of 802.11b WLAN is 11 Mbps while the actual speed is around 6 Mbps only [84]. Therefore, the throughput gives the actual speed at which the data can be transmitted.

Bandwidth

Though a bandwidth originally refers to a measure of a width of frequency range often used quite frequently in the world of digital communication, in recent years many people have been using the term bandwidth to refer to the channel capacity of a digital communication line [85]. In addition, the terms "bandwidth" and "throughput" are used interchangeably quite often these days. But there are some key differences between these two terms.

Bandwidth is the total channel capacity, which refers to the maximum rate at which data can be transferred over a given link. Throughput is the amount of

the capacity that the system actually utilizes in that given period. Throughput refers to the actual speed over the communication link. For a given system, depending upon the time and the physical infrastructure of the link or network throughout may differ accordingly. However, the bandwidth remains constant for a given system. A quick glance of some of the differences between bandwidth and throughput is given below in Table 8-1 [86].

Table 8-1 Bandwidth vs throughput.

BANDWIDTH	THROUGHPUT
How fast a device can send data over a single communication channel	How fast a device is actually sending data over a single communication channel
Independent of link distance	Varies with link distance
Bandwidth ≥ Throughput	Throughput ≤ Bandwidth
Also called maximum throughput	Also called consumed bandwidth
Theoretical case	Practical case

8.1 Throughput Test Experiments

As already discussed earlier that the throughput is the main metric for the performance of any wired or wireless network, hence it is worth performing throughput experiments with various kinds of devices and changing various parameter settings. In this section, some throughput test experiments for various kinds of devices and their result analyses are presented .All the tests are carried out using an Iperf, a separate throughput measuring software and a Network speed tool, throughput-measuring tool of Nanostation2.

Iperf: Introduction

Iperf is a modern tool for network performance measurement written in C++ that can create TCP and User Datagram Protocol (UDP hereafter) data streams and measure the throughput of the network that is carrying them. Iperf has a client and server functionality, and can measure the throughput between the two ends, either in unidirectional or bi-directional. It allows users to set various parameters that can be used to testing a network or saying in another way it helps in optimizing a network [87-89].

The network performance is measured by running Iperf in two PCs connected with each other via either a network cable or a wireless medium. Generally 'with wire' means with a LAN Cat5 or Cat5e or Cat6 cable and 'without wire' means that the two PCs are in wireless connection. To start measuring throughput, one should run Iperf in Client mode in one PC (sender) and in Server mode in another PC (receiver).

Since the client PC sends the data and the server PC receives them, they are also known as "sender" and "receiver" respectively. After everything is setup, a file (larger file is better) is transferred from client PC to the server PC using the following two different Iperf commands in two PCs.

Server side:

```
iperf –s
```

Client side:

```
iperf –c [Server PC IP Address] –F [file name]
```

After a successful transfer of the file, the Iperf running window outputs a display of a time stamp showing the amount of data transferred and the corresponding throughput measured of the link connecting the two PCs. The Iperf outputted result is as shown below in Table 8-2.

Table 8-2 A typical example of an Iperf outputted result window.

[ID]	*Interval*	*Transfer*	*Bandwidth*
[108]	*0.0-0.5 sec*	*634 MBytes*	*1.06 Gbits/s*
[108]	*5.0-10.0 sec*	*640 MBytes*	*1.07 Gbits/s*
[108]	*10.0-15.0 sec*	*647 MBytes*	*1.09 Gbits/s*
[108]	*15.0-20.0 sec*	*650 MBytes*	*1.09 Gbits/s*
[108]	*20.0-25.0 sec*	*645 MBytes*	*1.08 Gbits/s*
[108]	*25.0-30.0 sec*	*643 MBytes*	*1.08 Gbits/s*
[108]	*0.0-30.0 sec*	*3.77 GBytes*	*1.08 Gbits/s*

The above Table 8-2 is the output displayed by Iperf when a file of 3.77 Gbytes of size is transferred. There are total of four columns. The leftmost is the *ID* just indicating that the transmission is in uplink (from client to server) direction, the next to ID is Interval displaying time interval as set by the user, otherwise 10 sec is the default one. Next to Interval, the column Transfer contains the data values. In addition, the last one is Bandwidth representing the throughput value corresponding to the value displayed in Transfer column.

Iperf: Various Optional Arguments

By default, the Iperf client PC connects to the Iperf server PC on TCP port 5001 and the throughput displayed by Iperf is the throughput from client side to the server. However, there are various optional arguments applicable according to what is to be achieved. For example, if UDP throughput is to be measured rather than TCP, then the argument *-u* can be used and similarly *-n* can be used to transmit the data specifying the number of bits rather than the time argument *-t*. Some of the important Iperf arguments are listed below in Table 8-3 [87]:

Table 8-3 Iperf arguments and their purposes.

Arguments	Purpose
-s	Run in server mode
-c	Run in client mode
-u	UDP tests (use UDP rather than TCP)
-d	Simultaneous bidirectional bandwidth test
-r	Bidirectional bandwidth test individually
-t	Time in seconds to transmit
-i	Interval (seconds between periodic BW reports)
-f	Data format to report
-w	TCP window size (socket buffer size)
-F	File input
-n	Number of bytes to transmit (instead of -t)
-b	For UDP, bandwidth to send at in bits/s
-h	Help

8.1.1 Test for 100 Mbps Cat5 Cable

For testing the throughput of LAN cable, a 100 Mbps Cat5 cable is chosen. An experimental set-up is shown in the Figure-8-1 below.

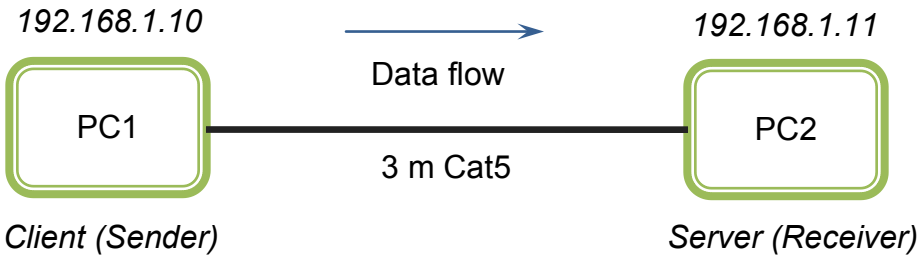


Figure 8-1 Throughput Test Setup for Cat5 Cable

As shown in Figure 8-1, an experiment was carried out to test the actual throughput of a 100 Mbps Cat5 cable. Two PCs are connected by 2 m Cat5 cable. The LAN IP address set to PC1 is 192.168.1.10 and PC2 is 192.168.1.11. Iperf is running in Client mode in PC1 and Server mode in PC2. Now for the test, the following command is entered in command prompt of PC2.

```
iperf -s
```

Using the following command in PC1, a video file of size 111 MBytes is sent from PC1 to PC2.

```
iperf –c 192.168.1.11 -F sg_video.mpg –i 1 –t 60
```

In above command, the IP address of destination or server (PC2) is entered after the argument *–c*. Similarly a video file “sg_video.mpg” is allowed to be sent using the argument *–F*. Other options such as *–i* and *–t* arguments determine the time interval for throughput report and the total time duration for

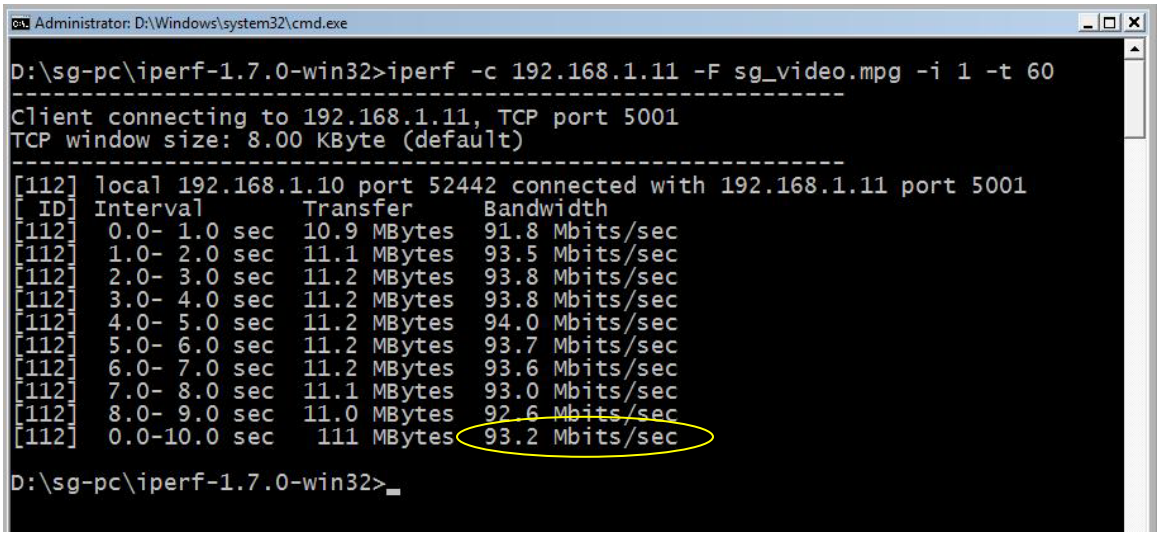

Administrator: D:\Windows\system32\cmd.exe
D:\sg-pc\iperf-1.7.0-win32>iperf -c 192.168.1.11 -F sg_video.mpg -i 1 -t 60
Client connecting to 192.168.1.11, TCP port 5001
TCP window size: 8.00 KByte (default)
[112] local 192.168.1.10 port 52442 connected with 192.168.1.11 port 5001
[ID] Interval Transfer Bandwidth
[112] 0.0- 1.0 sec 10.9 MBytes 91.8 Mbits/sec
[112] 1.0- 2.0 sec 11.1 MBytes 93.5 Mbits/sec
[112] 2.0- 3.0 sec 11.2 MBytes 93.8 Mbits/sec
[112] 3.0- 4.0 sec 11.2 MBytes 93.8 Mbits/sec
[112] 4.0- 5.0 sec 11.2 MBytes 94.0 Mbits/sec
[112] 5.0- 6.0 sec 11.2 MBytes 93.7 Mbits/sec
[112] 6.0- 7.0 sec 11.2 MBytes 93.6 Mbits/sec
[112] 7.0- 8.0 sec 11.1 MBytes 93.0 Mbits/sec
[112] 8.0- 9.0 sec 11.0 MBytes 92.6 Mbits/sec
[112] 0.0-10.0 sec 111 MBytes 93.2 Mbits/sec
D:\sg-pc\iperf-1.7.0-win32>

Figure 8-2 Throughput Result of Cat5 while Transferring Video File

the command to run. After entering the above command, a time stamped output as shown in above Figure 8-2 was output. Since interval is set 1 sec, the command outputs the throughput result every 1 sec and after the transfer of all 111 M Bytes, it outputs the aggregate throughput. For example, in the above experiment, while transferring the video file of 111 M Bytes, in first interval (i.e., 0.0-1.0 sec), it shows the output as 10.9 M Bytes of transferred and 91. 8 Mbits/sec of throughput. In addition, in second interval 1.0-2.0 sec, it shows the output of 11.1 MBytes of transferred and 93.5 Mbits/sec of throughput. Similarly, it reports the results every 1 second and finally when the transfer is complete, it shows the total aggregate throughput along with the total size of transferred file. Here in this experiment, the total size of file transferred is 111 MBytes in 10 sec with the aggregate throughput of 93.2 Mbits/sec.

8.1.2 Test for Wireless Router

For the throughput test of a wireless router, an Actiontec GT704WG router, which uses Verizon high speed internet service, is chosen. An experimental set-up is shown in Figure-8-3 below.

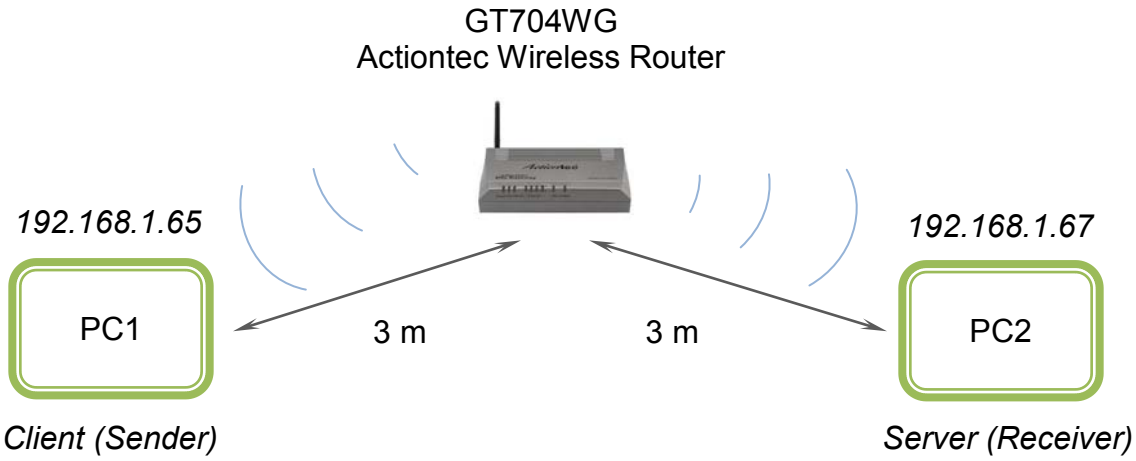


Figure 8-3 Throughput Test Setup for Wireless Router

As shown in Figure 8-3, an experiment was carried out to test the actual throughput of a wireless router being served by Verizon high speed internet. A GT704WG wireless DSL modem manufactured by Actiontec is used for this experiment. The two PCs are in WLAN connection connected by the wireless router. The WLAN IP address set to PC1 is 192.168.1.65 and PC2 is 192.168.1.67. Iperf is running in Client mode in PC1 and Server mode in PC2. Now for the test, the following command is entered in command prompt of PC2.

```
iperf -s
```

Using the following command in PC1, a video file of size 111 MBytes is sent from PC1 to PC2.

iperf –c 192.168.1.67 -F sg_video.mpg –i 1 –t 60

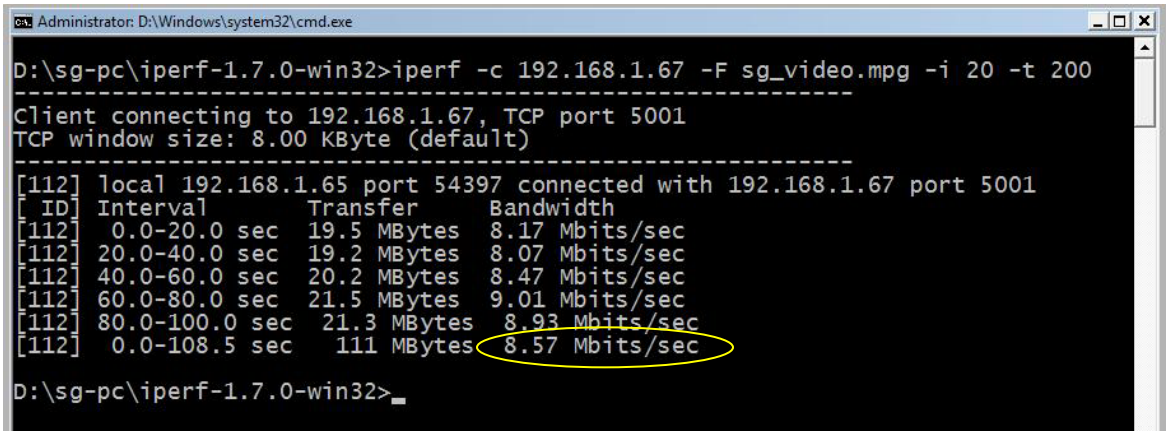

Administrator: D:\Windows\system32\cmd.exe
D:\sg-pc\iperf-1.7.0-win32>iperf -c 192.168.1.67 -F sg_video.mpg -i 20 -t 200
Client connecting to 192.168.1.67, TCP port 5001
TCP window size: 8.00 KByte (default)
[112] local 192.168.1.65 port 54397 connected with 192.168.1.67 port 5001
[ID] Interval Transfer Bandwidth
[112] 0.0-20.0 sec 19.5 MBytes 8.17 Mbits/sec
[112] 20.0-40.0 sec 19.2 MBytes 8.07 Mbits/sec
[112] 40.0-60.0 sec 20.2 MBytes 8.47 Mbits/sec
[112] 60.0-80.0 sec 21.5 MBytes 9.01 Mbits/sec
[112] 80.0-100.0 sec 21.3 MBytes 8.93 Mbits/sec
[112] 0.0-108.5 sec 111 MBytes 8.57 Mbits/sec
D:\sg-pc\iperf-1.7.0-win32>

Figure 8-4 Throughput Result of Wireless Router while Transferring Video File

After entering the above command, a time stamped output as shown in above Figure 8-4 was outputted. Here in this experiment, the total size of file transferred is 111 MBytes with the aggregate throughput of 8.57 Mbits/sec for which the total transfer time of 108.5 sec.

8.1.3 Test for Nanostation2

For testing the throughput of Nanostation2, there are two options. Change in throughput can be observed one by varying the Tx power and another by varying data rate of Nanostation2. The following are the experiments carried out for the measurement of throughput of Nanostation2. An experimental setup is shown in Figure 8-5.

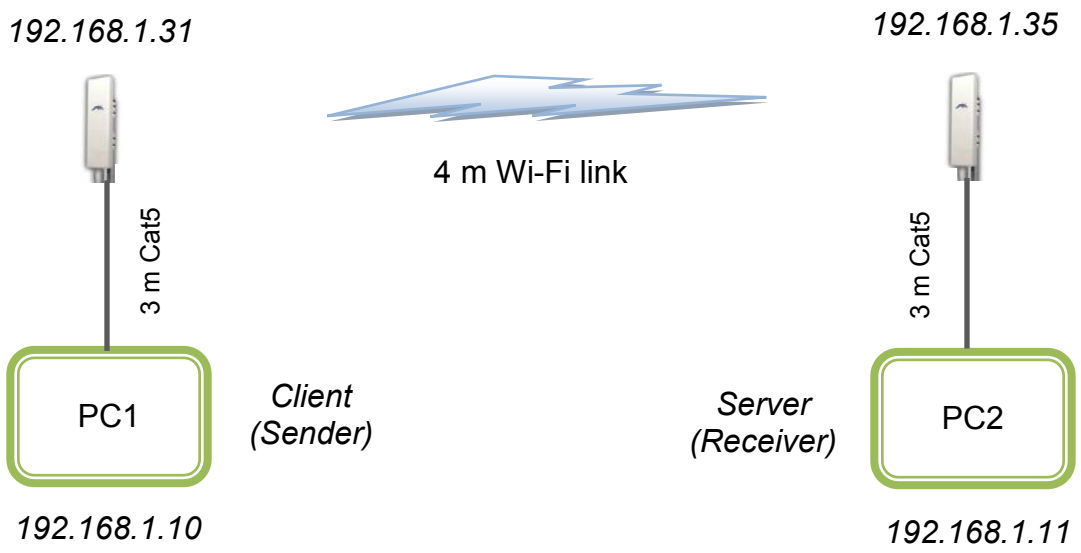


Figure 8-5 Throughput Test Setup for Nanostation2

IP addresses of PC1 and PC2 are 192.168.1.10 and 192.168.1.11 respectively. The PC1 is connected to its Nanostation2 whose IP address is 192.168.1.31 with Cat5 cable and PC2 is connected to its Nanostation2 whose IP address is 192.168.1.35 as shown in above Figure 8-5. The cables are only 3 m long. The experiment is carried out inside a room where the nanostations are kept 4 m apart with a perfect line of sight. Several experiments will be discussed keeping the physical positions of the nanostations unchanged but changing some parameters of Nanostation2. That means all the experiments that will be discussed in this Section 8.1.3 will refer to the same experimental setup shown in Figure 8-5.

Now, several experimental results obtained by using Iperf will be discussed. A video file "video3.wmv" of size 42.9 M Bytes is transferred and recorded the output throughput every time changing data rate and Tx power.

Experiment 1: Parameters Settings

Tx power = 11 dBm

Data Rate = 13.5 Mbps

Rate Mode = Quarter

RSL = -16 dBm

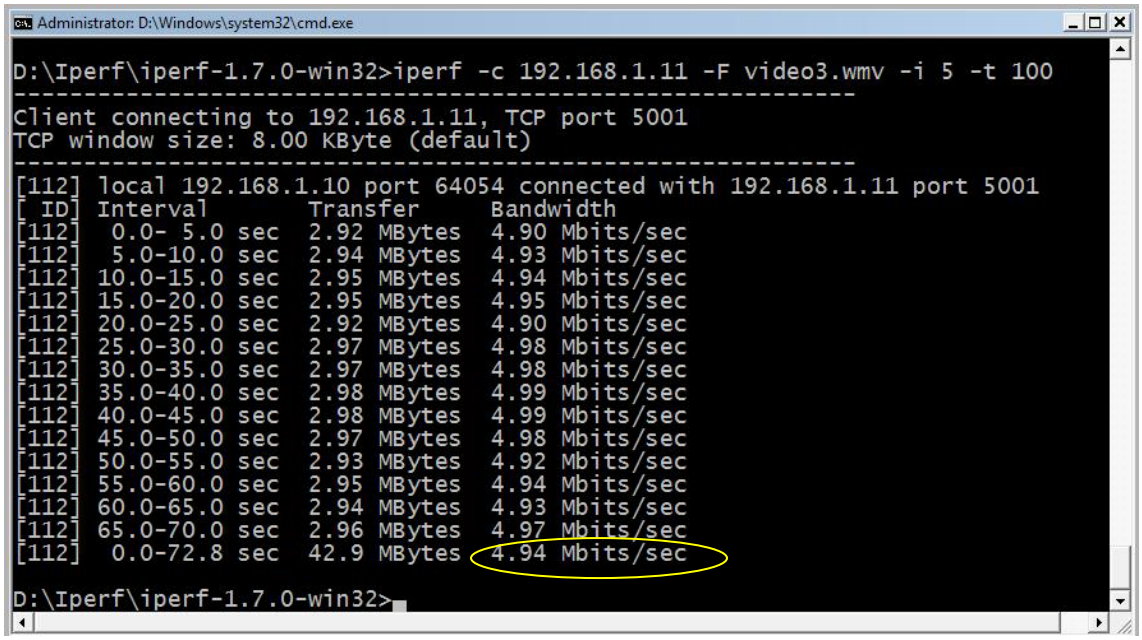

Administrator: D:\Windows\system32\cmd.exe
D:\Iperf\iperf-1.7.0-win32>iperf -c 192.168.1.11 -F video3.wmv -i 5 -t 100
Client connecting to 192.168.1.11, TCP port 5001
TCP window size: 8.00 KByte (default)
[112] local 192.168.1.10 port 64054 connected with 192.168.1.11 port 5001
[ID] Interval Transfer Bandwidth
[112] 0.0- 5.0 sec 2.92 MBytes 4.90 Mbits/sec
[112] 5.0-10.0 sec 2.94 MBytes 4.93 Mbits/sec
[112] 10.0-15.0 sec 2.95 MBytes 4.94 Mbits/sec
[112] 15.0-20.0 sec 2.95 MBytes 4.95 Mbits/sec
[112] 20.0-25.0 sec 2.92 MBytes 4.90 Mbits/sec
[112] 25.0-30.0 sec 2.97 MBytes 4.98 Mbits/sec
[112] 30.0-35.0 sec 2.97 MBytes 4.98 Mbits/sec
[112] 35.0-40.0 sec 2.98 MBytes 4.99 Mbits/sec
[112] 40.0-45.0 sec 2.98 MBytes 4.99 Mbits/sec
[112] 45.0-50.0 sec 2.97 MBytes 4.98 Mbits/sec
[112] 50.0-55.0 sec 2.93 MBytes 4.92 Mbits/sec
[112] 55.0-60.0 sec 2.95 MBytes 4.94 Mbits/sec
[112] 60.0-65.0 sec 2.94 MBytes 4.93 Mbits/sec
[112] 65.0-70.0 sec 2.96 MBytes 4.97 Mbits/sec
[112] 0.0-72.8 sec 42.9 MBytes 4.94 Mbits/sec
D:\Iperf\iperf-1.7.0-win32>

Figure 8-6 Throughput Result of Experiment 1

Experiment 2: Parameters Settings

Tx power = 26 dBm

Data Rate = 13.5 Mbps

Rate Mode = Quarter

RSL = -1 dBm

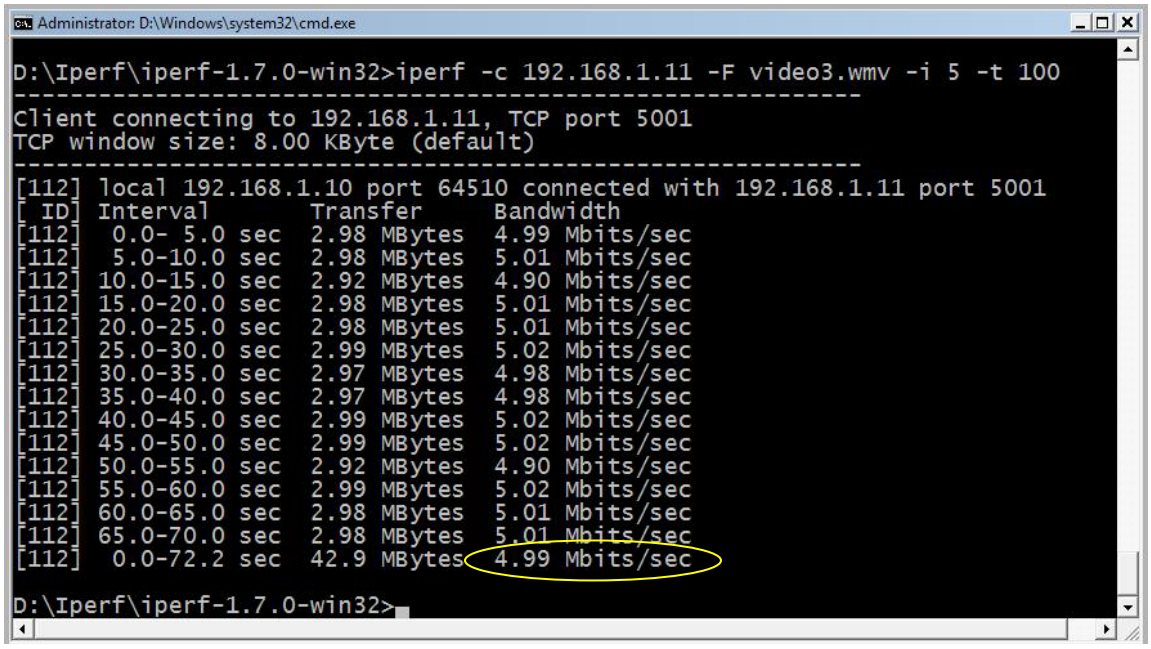

Administrator: D:\Windows\system32\cmd.exe
D:\Iperf\iperf-1.7.0-win32>iperf -c 192.168.1.11 -F video3.wmv -i 5 -t 100
Client connecting to 192.168.1.11, TCP port 5001
TCP window size: 8.00 KByte (default)
[112] local 192.168.1.10 port 64510 connected with 192.168.1.11 port 5001
[ID] Interval Transfer Bandwidth
[112] 0.0- 5.0 sec 2.98 MBytes 4.99 Mbits/sec
[112] 5.0-10.0 sec 2.98 MBytes 5.01 Mbits/sec
[112] 10.0-15.0 sec 2.92 MBytes 4.90 Mbits/sec
[112] 15.0-20.0 sec 2.98 MBytes 5.01 Mbits/sec
[112] 20.0-25.0 sec 2.98 MBytes 5.01 Mbits/sec
[112] 25.0-30.0 sec 2.99 MBytes 5.02 Mbits/sec
[112] 30.0-35.0 sec 2.97 MBytes 4.98 Mbits/sec
[112] 35.0-40.0 sec 2.97 MBytes 4.98 Mbits/sec
[112] 40.0-45.0 sec 2.99 MBytes 5.02 Mbits/sec
[112] 45.0-50.0 sec 2.99 MBytes 5.02 Mbits/sec
[112] 50.0-55.0 sec 2.92 MBytes 4.90 Mbits/sec
[112] 55.0-60.0 sec 2.99 MBytes 5.02 Mbits/sec
[112] 60.0-65.0 sec 2.98 MBytes 5.01 Mbits/sec
[112] 65.0-70.0 sec 2.98 MBytes 5.01 Mbits/sec
[112] 0.0-72.2 sec 42.9 MBytes 4.99 Mbits/sec
D:\Iperf\iperf-1.7.0-win32>

Figure 8-7 Throughput Result of Experiment 2

Experiment 3: Parameters Settings

Tx power = 11 dBm

Data Rate = 54 Mbps

Rate Mode = Full

RSL = -22 dBm

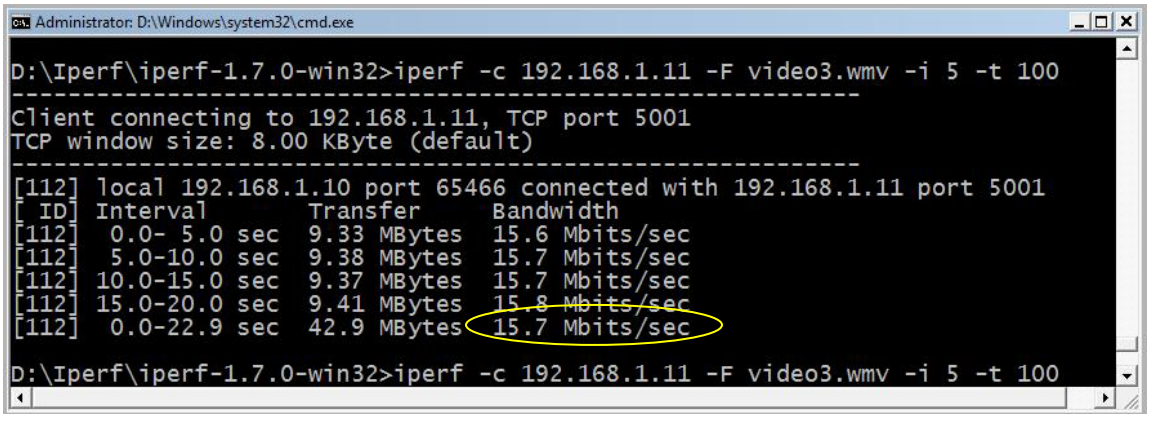

Administrator: D:\Windows\system32\cmd.exe
D:\Iperf\iperf-1.7.0-win32>iperf -c 192.168.1.11 -F video3.wmv -i 5 -t 100
Client connecting to 192.168.1.11, TCP port 5001
TCP window size: 8.00 KByte (default)
[112] local 192.168.1.10 port 65466 connected with 192.168.1.11 port 5001
[ID] Interval Transfer Bandwidth
[112] 0.0- 5.0 sec 9.33 MBytes 15.6 Mbits/sec
[112] 5.0-10.0 sec 9.38 MBytes 15.7 Mbits/sec
[112] 10.0-15.0 sec 9.37 MBytes 15.7 Mbits/sec
[112] 15.0-20.0 sec 9.41 MBytes 15.8 Mbits/sec
[112] 0.0-22.9 sec 42.9 MBytes 15.7 Mbits/sec
D:\Iperf\iperf-1.7.0-win32>iperf -c 192.168.1.11 -F video3.wmv -i 5 -t 100

Figure 8-8 Throughput Result of Experiment 3

Experiment 4: Parameters Settings

Tx power = 26 dBm

Data Rate = 54 Mbps

Rate Mode = Full

RSL = -4 dBm

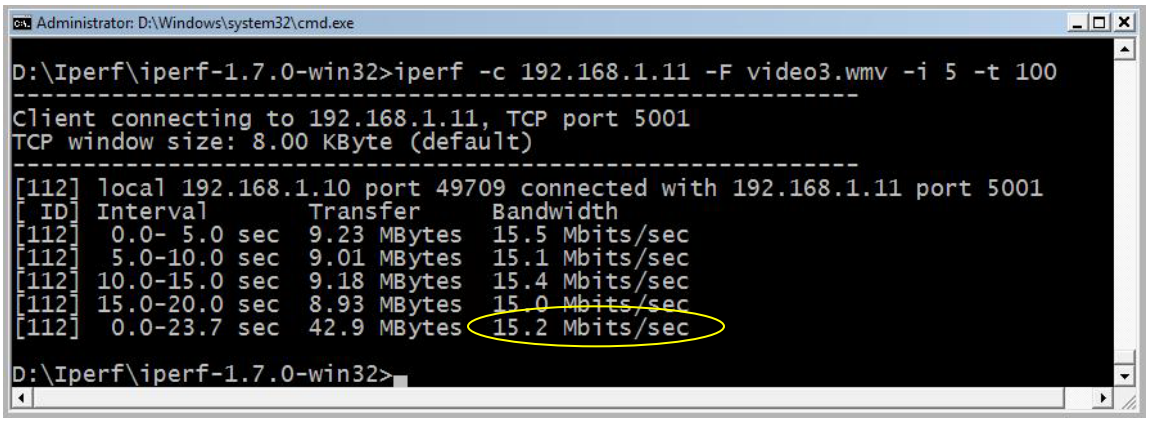

Administrator: D:\Windows\system32\cmd.exe
D:\Iperf\iperf-1.7.0-win32>iperf -c 192.168.1.11 -F video3.wmv -i 5 -t 100
Client connecting to 192.168.1.11, TCP port 5001
TCP window size: 8.00 KByte (default)
[112] local 192.168.1.10 port 49709 connected with 192.168.1.11 port 5001
[ID] Interval Transfer Bandwidth
[112] 0.0- 5.0 sec 9.23 MBytes 15.5 Mbits/sec
[112] 5.0-10.0 sec 9.01 MBytes 15.1 Mbits/sec
[112] 10.0-15.0 sec 9.18 MBytes 15.4 Mbits/sec
[112] 15.0-20.0 sec 8.93 MBytes 15.0 Mbits/sec
[112] 0.0-23.7 sec 42.9 MBytes 15.2 Mbits/sec
D:\Iperf\iperf-1.7.0-win32>

Figure 8-9 Throughput Result of Experiment 4

Observations of Above Experiments:

- Observation 1: Effect of change in Tx power on throughput

The two obtained throughout results for two different Tx powers are as follows:

Experiment 1 – 4.94 Mbits/sec at Tx power=11 dBm, Data Rate=13.5 Mbps

Experiment 2 – 4.99 Mbits/sec at Tx power=26 dBm, Data Rate=13.5 Mbps

The results didn't show a significant difference in the two throughput values. The rationale behind this may be because the two nanostations are kept only at a distance of 4 m and 11 dBm of Tx power is quite enough to provide

sufficient amount of RSL (-16 dBm) which obviously affect the throughout. That's why only a small improvement in RSL (-1 dBm) as well as in throughput is obtained even after a huge increment of Tx power (i.e., from 11 dBm to 26 dBm). But this is for sure that if the experiment is carried out with a longer link distance (let's say about 5 km), the results will show a significant difference in RSL as well as in throughput values. Hence it can be concluded that increasing Tx power of Nanostation2 can definitely result in greater throughout of the wireless link.

- Observation 2: Effect of change in data rate on throughput

The two obtained throughout results for two different data rates are as follows:

Experiment 1 - 4.94 Mbits/sec at Data Rate=13.5 Mbps, Tx power=11 dBm

Experiment 3 – 15.7 Mbits/sec at Data Rate=54 Mbps, Tx power=11 dBm

Observing the obtained results of Experiment 1 and Experiment 3, a significant difference in the two throughput values can be observed while changing data rate from 13.5 Mbps to 54 Mbps. Hence it can easily be concluded that increasing data rate of Nanostation2 can result in greater throughout of the wireless link

Experiment 4 – 15.2 Mbits/sec at Data Rate=54 Mbps, Tx power=26 dBm

Another observation similar to Observation 1 can be analyzed by comparing the results of Experiment 3 and Experiment 4. No improvement in throughput performance is seen even when the Tx power is increased from 11 dBm to 26 dBm. The reason is same as explained in Observation 1.

8.2 Throughput Measurement of EESAT_NS2 - DPWS_NS2 Link

In this section, the throughput measurement of the radio link between EESAT_NS2 and DPWS_NS2 is discussed. For measuring the throughput for this link, the various results obtained using two different network performance measuring tools are analyzed and discussed. The tools used are Iperf and network speed test tool of Nanostation2 and then those results are compared.

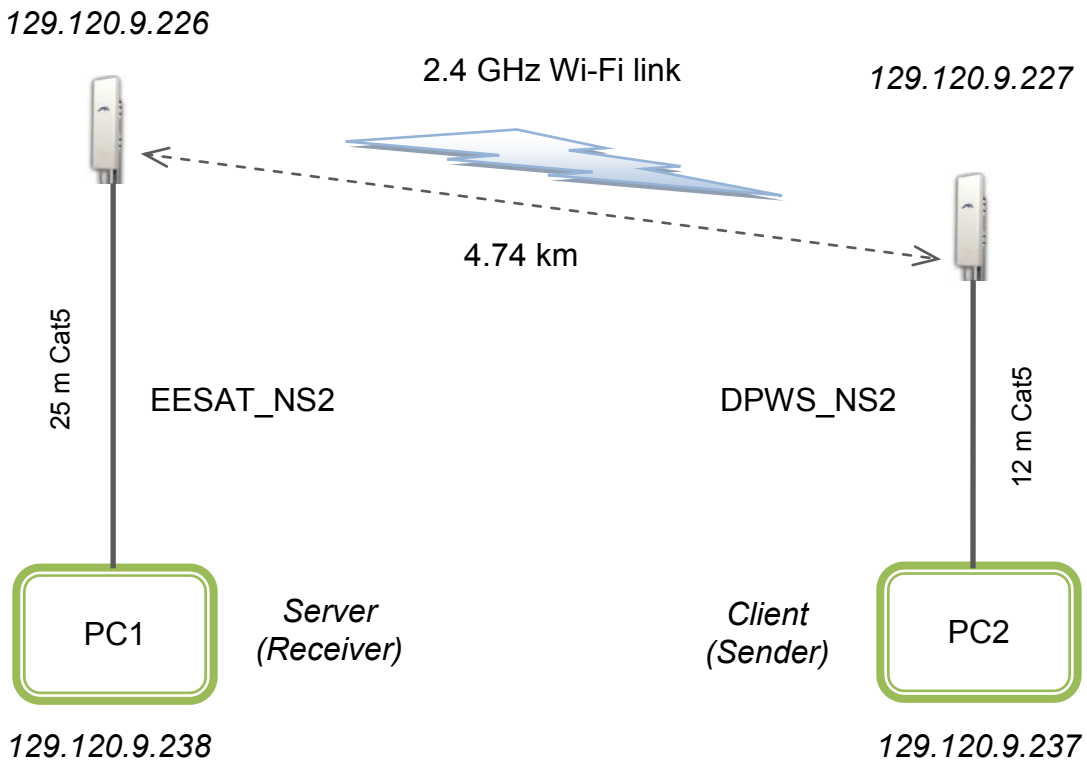


Figure 8-10 Throughput Test Setup for EESAT_NS2-DPWS_NS2 Link

For the test, each Nanostation2 is connected to a PC in either site as shown in the Figure 8-10 above. The EESAT_NS2 is connected to PC1 that is running Iperf in server mode and DPWS_NS2 to PC2 that is running Iperf in

client mode. The IP addresses of EESAT_NS2 and DPWS_NS2 are set as 129.120.9.226 and 129.120.9.227 respectively. Similarly, IP addresses of PC1 and PC2 are set as 129.120.9.238 and 129.120.9.237 respectively. The two nanostations are 4.74 km apart from each other. EESAT_NS2 and DPWS_NS2 are connected to the PC1and PC2 by 25 m and 12 m Cat5 cables respectively.

Now various throughput results obtained using Iperf first by changing Tx power and then by changing data rate will be discussed. In addition, in order to tally the results for their accuracy, the tests are repeated using network speed test tool. For all the experiments that are going to performed, all the physical set up shown in Figure 8-10 will be kept unchanged. All the experiments discussed in this Section 8.2 will refer to the same experimental setup shown in Figure 8-9.

8.2.1 Throughput Measurements Using Iperf

In this section, throughout measurements of EESAT_NS2 – DPWS_NS2 link using Iperf are performed. First two tests at two different Tx powers: one at 11 dBm and another at 26 dBm will be performed. Then another two tests at two different data rates: one at 13.5 Mbps and another at 54 Mbps will be performed. The first two tests are performed to figure out the effect of change of transmitted power on the throughput. In addition, the results of the latter two tests help how the throughput changes as the data rates are varied. An audio file (audio.mp3) of size 12 M Bytes is sent for 60 seconds from PC2 to PC1 and the throughput results are recorded.

The Iperf command used for the throughput measurements for all the four experiments is as follows:

```
iperf –c 129.120.0.238 –F audio.mp3 –i 10 –t 60
```

Experiment 8.2.1-1: Parameters Settings

Table 8-4 Throughput Expt. 8.2.1-1: Parameters settings.

PARAMETERS	EESAT_NS2	DPWS_NS2
Iperf mode	Server	Client
Tx power	11 dBm	
Data Rate	13.5 Mbps	
Rate Mode	Quarter (5 MHz)	
RSL	-86 dBm	

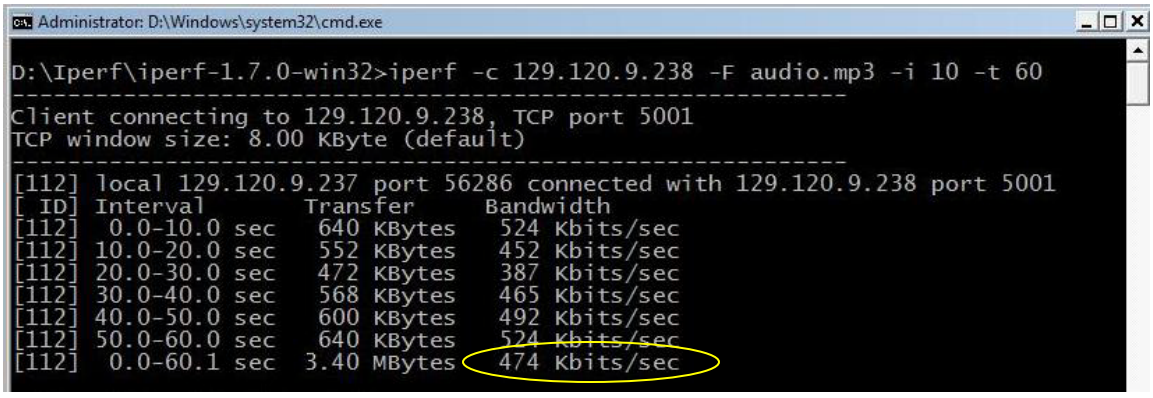

Administrator: D:\Windows\system32\cmd.exe
D:\Iperf\iperf-1.7.0-win32>iperf -c 129.120.9.238 -F audio.mp3 -i 10 -t 60
Client connecting to 129.120.9.238, TCP port 5001
TCP window size: 8.00 KByte (default)
[112] local 129.120.9.237 port 56286 connected with 129.120.9.238 port 5001
[ID] Interval Transfer Bandwidth
[112] 0.0-10.0 sec 640 KBytes 524 Kbits/sec
[112] 10.0-20.0 sec 552 KBytes 452 Kbits/sec
[112] 20.0-30.0 sec 472 KBytes 387 Kbits/sec
[112] 30.0-40.0 sec 568 KBytes 465 Kbits/sec
[112] 40.0-50.0 sec 600 KBytes 492 Kbits/sec
[112] 50.0-60.0 sec 640 KBytes 524 Kbits/sec
[112] 0.0-60.1 sec 3.40 MBytes 474 Kbits/sec

Figure 8-11 Throughput Result of Experiment 8.2.1-1

Result: Throughput = 474 Kbits/sec

Experiment 8.2.1-2: Parameters Settings

Table 8-5 Throughput Expt. 8.2.1-2: Parameters settings.

PARAMETERS	EESAT_NS2	DPWS_NS2
Iperf mode	Server	Client
Tx power	26 dBm	
Data Rate	13.5 Mbps	
Rate Mode	Quarter (5 MHz)	
RSL	-66 dBm	

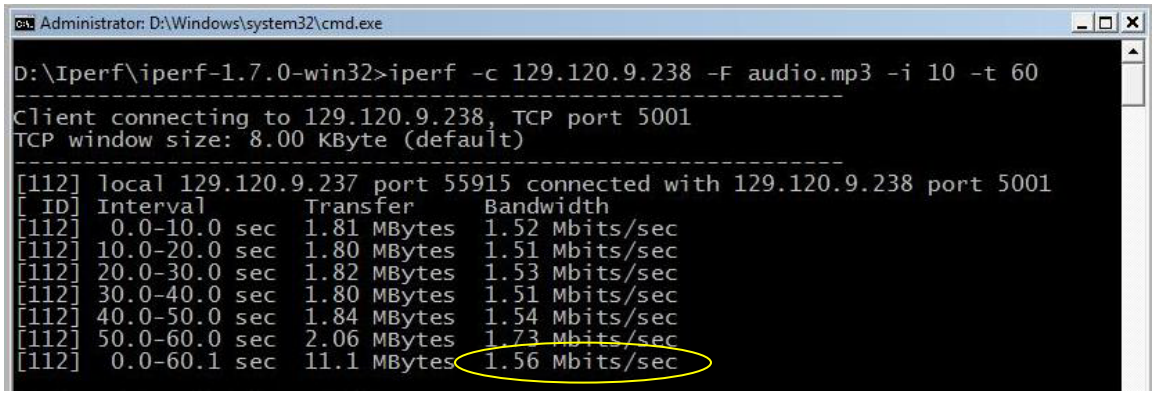

Administrator: D:\Windows\system32\cmd.exe
D:\Iperf\iperf-1.7.0-win32>iperf -c 129.120.9.238 -F audio.mp3 -i 10 -t 60
Client connecting to 129.120.9.238, TCP port 5001
TCP window size: 8.00 KByte (default)
[112] local 129.120.9.237 port 55915 connected with 129.120.9.238 port 5001
[ID] Interval Transfer Bandwidth
[112] 0.0-10.0 sec 1.81 MBytes 1.52 Mbits/sec
[112] 10.0-20.0 sec 1.80 MBytes 1.51 Mbits/sec
[112] 20.0-30.0 sec 1.82 MBytes 1.53 Mbits/sec
[112] 30.0-40.0 sec 1.80 MBytes 1.51 Mbits/sec
[112] 40.0-50.0 sec 1.84 MBytes 1.54 Mbits/sec
[112] 50.0-60.0 sec 2.06 MBytes 1.73 Mbits/sec
[112] 0.0-60.1 sec 11.1 MBytes 1.56 Mbits/sec

Figure 8-12 Throughput Result of Experiment 8.2.1-2

Result: Throughput = 1.56 Mbits/sec

Experiment 8.2.1-3: Parameters Settings

Table 8-6 Throughput Expt. 8.2.1-3: Parameters settings.

PARAMETERS	EESAT_NS2	DPWS_NS2
Iperf mode	Server	Client
Tx power	11 dBm	
Data Rate	54 Mbps	
Rate Mode	Full (20 MHz)	
RSL	-89 dBm	

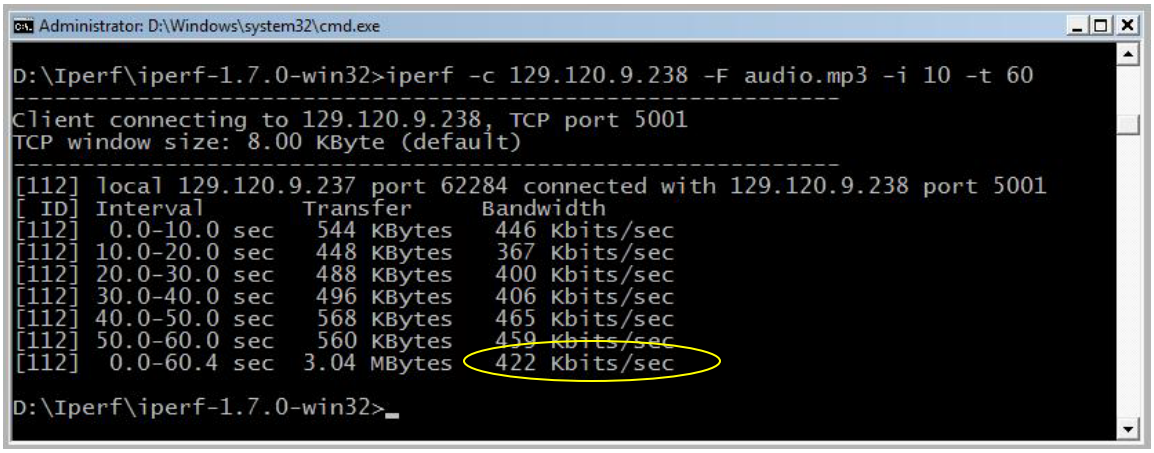

Administrator: D:\Windows\system32\cmd.exe
D:\Iperf\iperf-1.7.0-win32>iperf -c 129.120.9.238 -F audio.mp3 -i 10 -t 60
Client connecting to 129.120.9.238, TCP port 5001
TCP window size: 8.00 KByte (default)
[112] local 129.120.9.237 port 62284 connected with 129.120.9.238 port 5001
[ID] Interval Transfer Bandwidth
[112] 0.0-10.0 sec 544 KBytes 446 Kbits/sec
[112] 10.0-20.0 sec 448 KBytes 367 Kbits/sec
[112] 20.0-30.0 sec 488 KBytes 400 Kbits/sec
[112] 30.0-40.0 sec 496 KBytes 406 Kbits/sec
[112] 40.0-50.0 sec 568 KBytes 465 Kbits/sec
[112] 50.0-60.0 sec 560 KBytes 459 Kbits/sec
[112] 0.0-60.4 sec 3.04 MBytes 422 Kbits/sec
D:\Iperf\iperf-1.7.0-win32>

Figure 8-13 Throughput Result of Experiment 8.2.1-3

Result: Throughput = 422 Kbits/sec

Experiment 8.2.1-4: Parameters Settings

Table 8-7 Throughput Expt. 8.2.1-4: Parameters settings.

PARAMETERS	EESAT_NS2	DPWS_NS2
Iperf mode	Server	Client
Tx power	26 dBm	
Data Rate	54 Mbps	
Rate Mode	Full (20 MHz)	
RSL	-71 dBm	

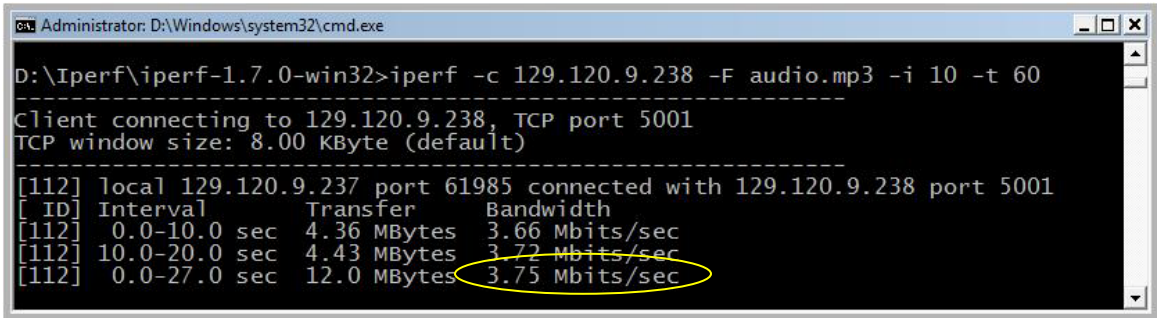

Administrator: D:\Windows\system32\cmd.exe
D:\Iperf\iperf-1.7.0-win32>iperf -c 129.120.9.238 -F audio.mp3 -i 10 -t 60
Client connecting to 129.120.9.238, TCP port 5001
TCP window size: 8.00 KByte (default)
[112] local 129.120.9.237 port 61985 connected with 129.120.9.238 port 5001
[ID] Interval Transfer Bandwidth
[112] 0.0-10.0 sec 4.36 MBytes 3.66 Mbits/sec
[112] 10.0-20.0 sec 4.43 MBytes 3.72 Mbits/sec
[112] 0.0-27.0 sec 12.0 MBytes 3.75 Mbits/sec

Figure 8-14 Throughput Result of Experiment 8.2.1-4

Result: Throughput = 3.75 Mbits/sec

Observations and Analyses of Above Experiments:

Now, let's discuss about how the settings of the parameters such as Tx power and data rate affect the throughput performance of the system. The obtained throughout results for two different Tx powers and the two different data rates are summarized as follows:

Experiment 8.2.1-1 – 474 Kbits/sec at Tx power=11 dBm, Data Rate=13.5 Mbps

Experiment 8.2.1-2 – 1.56 Mbits/sec at Tx power=26 dBm, Data Rate=13.5 Mbps

Experiment 8.2.1-3 – 422 Kbits/sec at Data Rate=54 Mbps, Tx power=11 dBm

Experiment 8.2.1-4 – 3.75 Mbits/sec at Data Rate=54 Mbps, Tx power=26 dBm

- Observation 1: Effect of change in Tx power on throughput

The huge and significant difference in the results of the Experiments 8.2.1-1 and Experiment 8.2.1-2 shows that the impact of Tx power is very noticeable for longer link such as 4.74 km EESAT_NS2 – DPWS_NS2 radio link.

- Observation 2: Effect of change in Data Rate on throughput

i) Effect of change in data rate on throughput at high Tx power (26 dBm)

From the results of the experiments Experiment 8.2.1-2 and Experiment 8.2.1-4, it is clearly noticeable that the throughput is improved significantly when the data rate is increased from 13.5 Mbps to 54 Mbps keeping the Tx power constant at 26 dBm.

ii) Effect of change in data rate on throughput at low Tx power (11 dBm)

There is no significant difference in the obtained throughput results of the experiments Experiment 8.2.1-1 and Experiment 8.2.1-3 even when the experiments are carried out at two contrasting data rates: one low and another high. The rationale behind this is the fact that insufficient Tx power always results a very low RSL which results lower throughput. As long as the RSL is not

obtained at sufficient amount, there's no use of increasing the data rate to get greater throughput.

- Observation 3: Effect of simultaneous change in Tx power and data rate on throughput

From the results of the experiments Experiment 8.2.1-1 and Experiment 8.2.1-4, it is clearly noticeable that the throughput is significantly increased from 474 Kbps to 3.75 Mbps when the Tx power is increased from 11 dBm to 26 dBm and the data rate is increased from 13.5 Mbps to 54 Mbps simultaneously.

8.2.2 Throughput Measurements Using Network Speed Test Tool

In this section also, at first the two tests at two different Tx powers: One at 11 dBm and another at 26 dBm are performed. Then the two tests at two different data rates: One at 13.5 Mbps and another at 54 Mbps are performed. All the tests are done setting EESAT_NS2 (129.120.9.226) as Tx and DPWS_NS2 (129.120.9.227) as Rx. That means the tests result the two throughputs: Tx and Rx throughputs where Tx throughput means the throughput from EESAT_NS2 to DPWS_NS2 and the RX throughput means the throughput from DPWS_NS2 to EESAT_NS2.

A data size of 12 MBytes (=12582912 Bytes) is sent for 60 seconds from PC2 to PC1 and the throughput results are recorded.

Experiment 8.2.2-1: Parameters Settings

Table 8-8 Throughput Expt. 8.2.2-1: Parameters settings.

PARAMETERS	EESAT_NS2	DPWS_NS2
Iperf mode	Server	Client
Tx power	11 dBm	
Data Rate	13.5 Mbps	
Rate Mode	Quarter (5 MHz)	
RSL	-86 dBm	

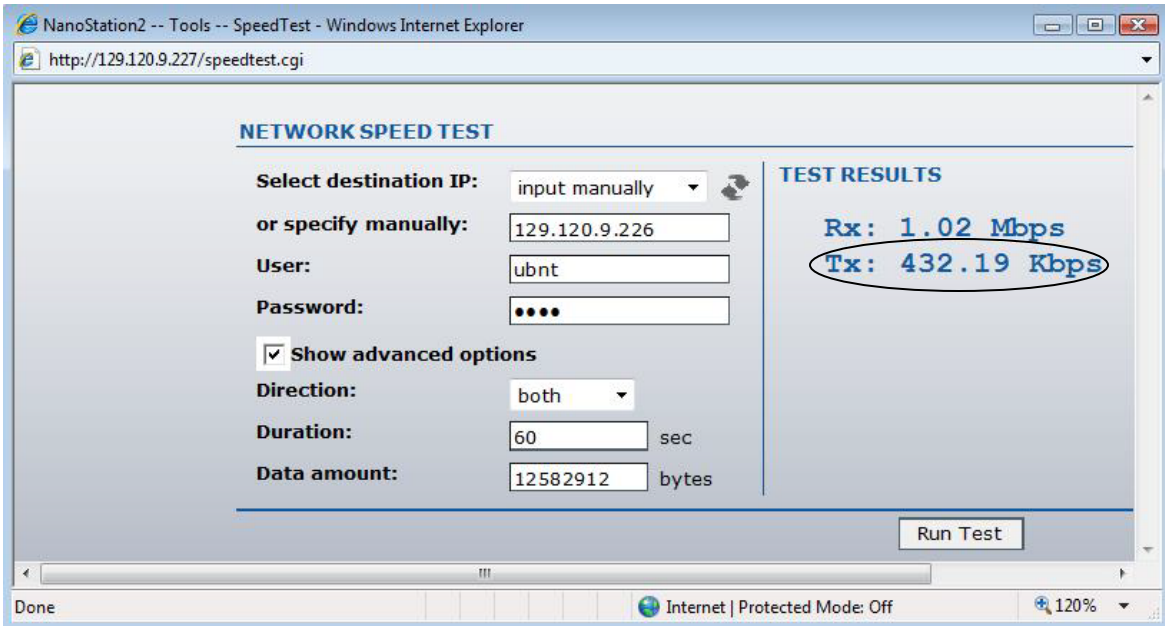


Figure 8-15 Throughput Result of Experiment 8.2.2-1

Result: Throughput = 432.19 Kbits/sec

Experiment 8.2.2-2: Parameters Settings

Table 8-9 Throughput Expt. 8.2.2-2: Parameters settings.

PARAMETERS	EESAT_NS2	DPWS_NS2
Iperf mode	Server	Client
Tx power	26 dBm	
Data Rate	13.5 Mbps	
Rate Mode	Quarter (5 MHz)	
RSL	-66 dBm	

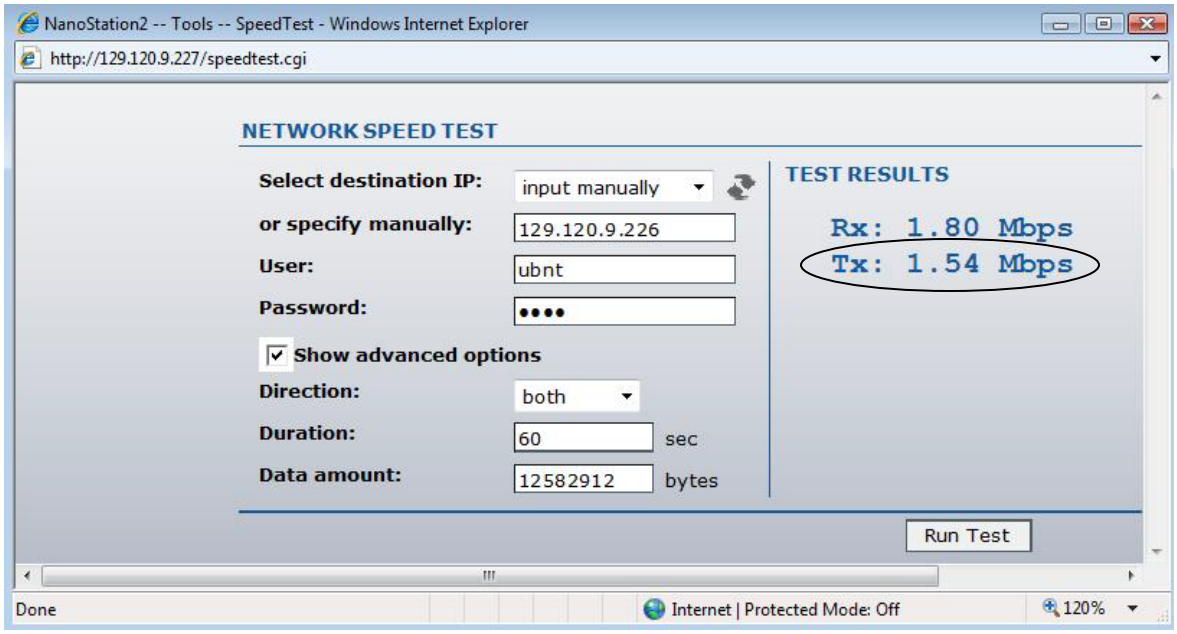


Figure 8-16 Throughput Result of Experiment 8.2.2-2

Result: Throughput = 1.54 Mbits/sec

Experiment 8.2.2-3: Parameters Settings

Table 8-10 Throughput Expt. 8.2.2-3: Parameters settings.

PARAMETERS	EESAT_NS2	DPWS_NS2
Iperf mode	Server	Client
Tx power	11 dBm	
Data Rate	54 Mbps	
Rate Mode	Full (20 MHz)	
RSL	-89 dBm	

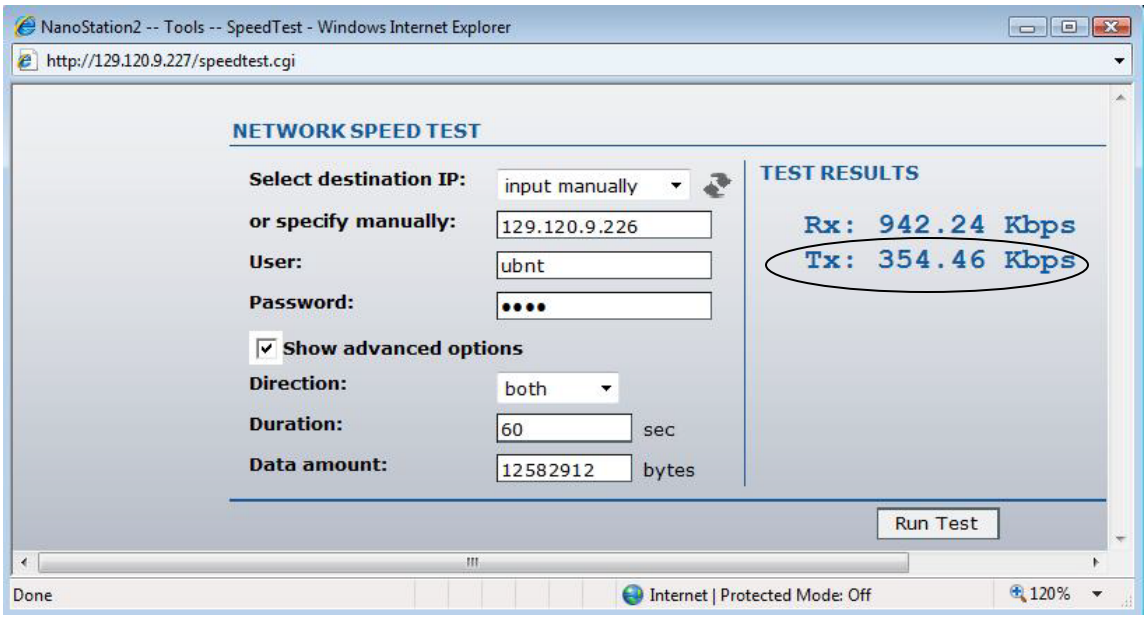


Figure 8-17 Throughput Result of Experiment 8.2.2-3

Result: Throughput = 354.46 Kbits/sec

Experiment 8.2.2-4: Parameters Settings

Table 8-11 Throughput Expt. 8.2.2-4: Parameters settings.

PARAMETERS	EESAT_NS2	DPWS_NS2
Iperf mode	Server	Client
Tx power	26 dBm	
Data Rate	54 Mbps	
Rate Mode	Quarter (5 MHz)	
RSL	-71 dBm	

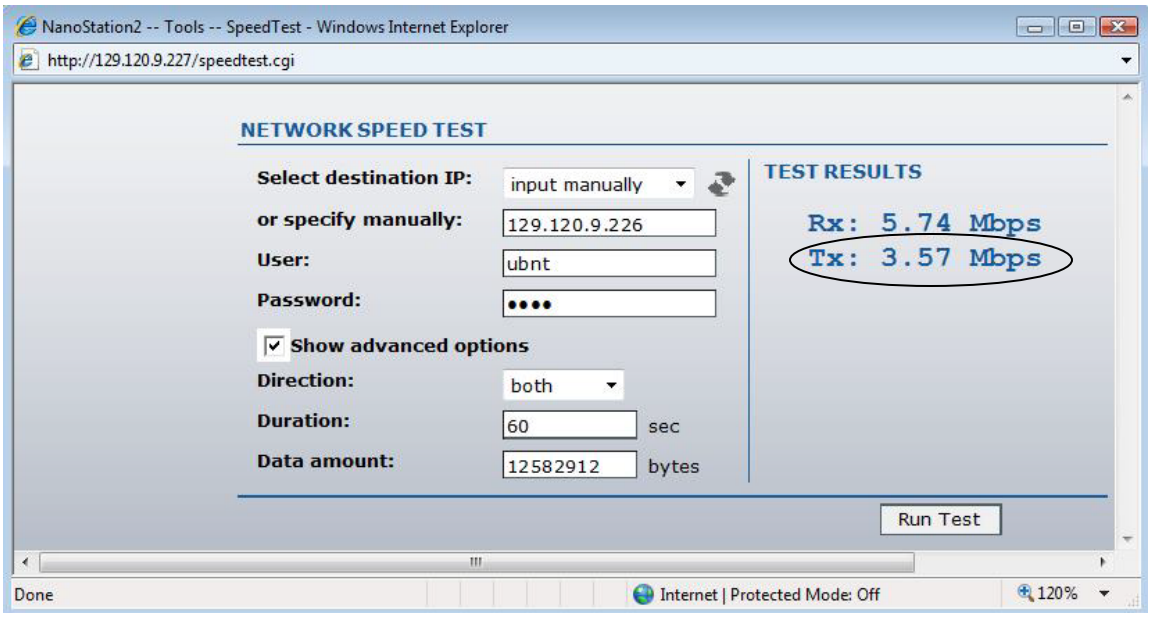


Figure 8-18 Throughput Result of Experiment 8.2.2-4

Result: Throughput = 3.57 Mbits/sec

Observations and Analyses of Above Experiments:

The obtained throughout results for two different Tx powers and the two different data rates are summarized as follows:

Experiment 8.2.2-1- 432.2 Kbits/sec at Tx power=11 dBm, Data Rate=13.5 Mbps

Experiment 8.2.2-2 – 1.54 Mbits/sec at Tx power=26 dBm, Data Rate=13.5 Mbps

Experiment 8.2.2-3 – 354.46 Kbits/sec at Data Rate=54 Mbps, Tx power=11 dBm

Experiment 8.2.2-4 – 3.57 Mbits/sec at Data Rate=54 Mbps, Tx power=26 dBm

- Observations:

All the throughput results are exactly similar as the results of the experiments done with Iperf discussed in Section 8.2.1. The only tiny difference is the numeral values, which differ in some magnitudes. Table 8-12 given below shows the throughout results obtained from using Iperf and Nanostation2 network speed test Tool.

Table 8-12 Throughput results of Iperf and network speed tool.

Link Distance	Tx Power	Data Rate	Throughput	
			Iperf	Network Speed Test Tool
4.74 Km	11 dBm	13.5 Mbps	474 Kbps	432.19 Kbps
	26 dBm	13.5 Mbps	1.56 Mbps	1.54 Mbps
	11 dBm	54 Mbps	422 Kbps	354.46 Kbps
	26 dBm	54 Mbps	3.75 Mbps	3.57 Mbps

8.3 Maximizing the Radio-Link Throughput Performance

The throughputs obtained in above discussed experiments are obviously affected by various external factors which degraded the throughput performance of the system. So in order to maximize the throughput of the system, first all the probable factors affecting the throughput are needed to be identified and then try to avoid or at least minimize those factors.

8.3.1 Various Factors Affecting Throughput Performance

There are various factors affecting the throughput of the WLAN system, but here only those factors affecting the present system will be discussed. The following are the probable factors that may contribute to degrade the throughput performance of the link between EESAT_NS2 and DPWS_NS2.

- *Interference due to other devices:* There may be different other devices (microwave, cordless phones, Bluetooth etc.) occupying same frequency spectrum or operating in 2.4 GHz band.
- *Inappropriate channel selection:* The present system may cause interference to UNT wireless and may receive interference especially from EESAT terrace
- *Data rate/rate algorithm settings:* If not matched with the obtained RSL (if RSL decreases somehow, then it reduces the data rate automatically to maintain the stability of the link)
- *Inappropriate spectral width settings:* Spectral width here in Nanostation2 means rate mode. Its selection can cause a significant difference in the

amount of interference that the system receives. There are three options for rate mode: Quarter (5 MHz), half (10 MHz) and full (20 MHz). Increasing rate mode obviously increases the throughput but it interferes a lot more than the smaller rate mode.

- *Distance between EESAT_NS2 (Tx) and DPWS_NS2 (Rx):* It is an inevitable factor due to which the maximum achievable throughput is decreased as the Tx-Rx separation goes on increasing.
- *Detrimental effect of combined B and G networks:* Operating in a mixed environment that includes 802.11b clients can substantially affect throughput. For example throughput of 802.11g networks may drop from 25 Mbps to 7 Mbps when 802.11b clients enter the environment [90].
- *Interference from high Tx power:* As throughput is directly dependent upon Tx power, every system wants to transmit at as much higher as possible knowingly or unknowingly causing interference to each other and hence degrading the throughput due to the interference from other system.

8.3.2 Techniques Used to Maximize the System Throughput

- *Interference:* Interference is one of the biggest contributors in degrading the throughput of the system. Interference from other systems, which are already operating on same frequency, is inevitable, but of course, could be minimized by appropriately setting different parameters of the system.

- *Channel selection:* Since one of the nanostations is installed on the terrace of EESAT building, it may cause interference to or receive from other UNT wireless systems. Therefore, it is extremely important to select the channel, which hasn't been used or least used. Channel 4 turned out to be the best channel to be selected for the system after analyzed by a Wi-Fi spectrum analyzing tool called AirView2.

- *Data rate/rate algorithm selection:* Depending upon the link quality condition, the Nanosation2 has the capacity to select the rate mode controlled by Rate Algorithm automatically. That means if the link quality is good then it selects the higher rate mode and switches to lower rate mode when it is poor [21]. But of course, higher rate mode can be set to have greater throughput but at the cost of probabilistic poor quality of link. But as far as the link EESAT_NS2 – DPWS_NS2 is concerned, the rate mode can be set higher in order to get a greater throughput because the link is pretty stable and robust having sufficient amount of fade margin.

- *Spectral width selection:* The spectral width selection can significantly affect the system throughput performance. Higher spectral width results in a greater throughput and vice versa. Therefore, its selection should also be done wisely depending upon the system demand and condition. Since there were already so much crowd in 2.4 GHz Wi-Fi channel, not to be severely affected and also not to affect other system severely, smallest available spectral width of 5 MHz is chosen for the system.

- *Selection of IEEE 802.11 mode:* A lot of Wi-Fi devices that are compatible with various IEEE standards are easily available in today's market. For example, the device compatible with both 802.11g and 802.11b standards can easily be found. Although this is good for interoperability, it is not always required. For example, when 802.11b excludes from the network in order to avoid unnecessary interference and thus achieve greater throughput.
- *Tx power settings:* As throughput increases as Tx power is increased, it is always good to transmit at high power but staying within the limit set by the country regulation. Besides that, it should also be made sure that other systems are not being affected by the high power used. However, a few amount of interference from and to other systems should be tolerable because the common unlicensed channel (2.4 GHz) is shared. For the link EESAT_NS2 – DPWS _NS2, since it is quite long (4.74 km) and the radiation is directional, the signal is transmitted at its highest power, i.e., at 26 dBm.

8.4 Impact of Data Rate on Throughput

Table 8-12 shows various results of the throughput experiments of the link EESAT_NS2 - DPWS_NS2 performed at different available 802.11g data rates. The two right most columns show the obtained Tx and Rx throughput results of the experiments carried out on the 5 MHz channel. And the Figure 8-19 is the graph of data rate vs throughput corresponding to the Table 8-12. The throughput experiment is carried out using network speed test tool of EESAT_NS2.

Table 8-13 Data rate vs throughput for IEEE802.11g.

IEEE Standard	EESAT_NS2	DPWS_NS2	Data Rate	Throughput (Tx)	Throughput (Rx)
802.11g	Server	Client	1.5 Mbps	1.03 Mbps	978.52 Kbps
	Access Point	Station	2.25 Mbps	1.76 Mbps	1.66 Mbps
			3 Mbps	1.85 Mbps	1.69 Mbps
	Tx power = 26 dBm		4.5 Mbps	2.36 Mbps	1.99 Mbps
	RSL = -62 to -69 dBm		6 Mbps	2.83 Mbps	2.03 Mbps
	Rate algorithm = Conservative		9 Mbps	3.13 Mbps	2.12 Mbps
			12 Mbps	3.21 Mbps	2.17 Mbps
			13.5 Mbps	3.28 Mbps	2.15 Mbps

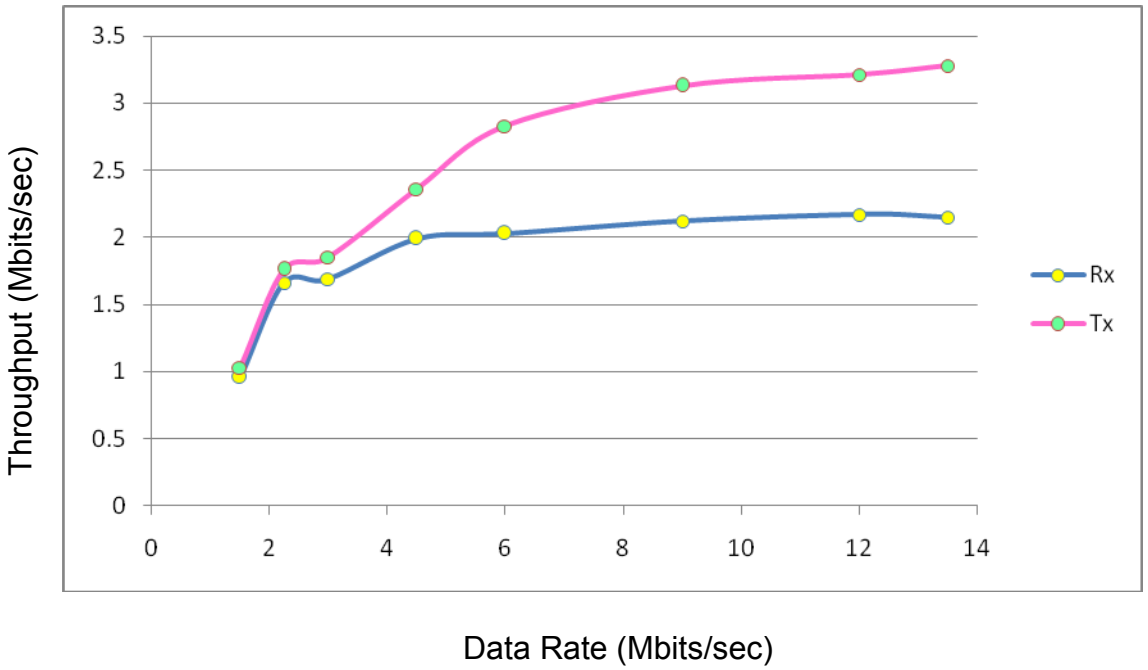


Figure 8-19 Data Rate Vs Throughput for IEEE802.11g

In the above Figure 8-19, the pink colored line denotes the Tx throughput (throughput from EESAT_NS2 to DPWS_NS2) and the blue colored denotes the Rx throughput (throughput from DPWS_NS2 to EESAT_NS2). The experiments are performed for all the available data rate settings for 802.11g. For every data rate settings, throughput values are measured 5 times and their average is taken. All the data values shown in the Table 8-12 are average data rates.

CHAPTER 9

CONCLUSION

Environmental data collection is accomplished by a weather and soil station (GBC_WS) in the forest of the Greenbelt Corridor A datalogger collects various environmental variables (such as air temperature, relative humidity, barometric air pressure, solar radiation, wind speed, wind direction, rainfall and soil moisture) every 15 minutes and pass the data to an SBC. This computer then transfers data to the server using a GPRS modem.

For transmitting data from the field to the server, an innovative high speed and a low cost Wi-Fi technology is used instead of the costly GPRS technology. For the implementation of this technology, a Nanostation2, a Wi-Fi compatible radio equipment having a built-in directional antenna is chosen. To test this concept a Wi-Fi radio link between EESAT where there is an internet source available and DP_WS is successfully implemented.

There are some future tasks recommended as a continuation of this work. Short term, is the interconnection of datalogger and Nanostation2 in order to access the datalogger and its data via internet. This will be done soon using an ethernet interface as discussed in Section 4.2.4.

One of the future plans is to establish a Wi-Fi radio link between GBC_WS and the Natural Heritage Center to collect the data of GBC WS via internet. An internet source is available in the Natural Heritage Center which is about 2.25 Km from GBC WS. The preliminary tests indicated lack of line of sight between these two sites because of the tall trees of the Greenbelt forest. The tests were conducted with a Nanostation2 attached to a 9 m pole in either site. It is estimated that a tall pole or a tower of at least 20 m height is required at both sites to have good LOS path.

This work may serve as reference for those who want to set up a radio link for any kind of application especially that require higher data throughput. And because the technology used is unlicensed throughout the world, this thesis can inspire work to deploy wireless internet service in remote and rural areas especially in developing countries.

APPENDIX A

EDLOG PROGRAM CODE FOR GBC_WS

i) Weather Station Program Code

```
;{CR10X}
;

; This program stores the time and all weather data in final
;   storage every fifteen minutes.  Rainfall is totaled for
;   the entire 15 minute interval.  The wind vector instruction
;   is used to store average wind speed and direction.  Also,
;   maximum wind speed is computed and stored.  Weather data are
;   transferred to the soil moisture data logger every fifteen
;   minutes, one minute after it is collected.  The time clock
;   of the weather logger is synchronized to that of the soil
;   moisture logger at 2:10 a.m. every morning.  The soil moisture
;   logger time is updated via cell modem once a day at 2:05 a.m.

*Table 1 Program
  01: 10        Execution Interval (seconds)

; The following instructions are executed at each execution cycle
;   to allow averaging over the 15 minute output period and, in
;   the case of rainfall, to detect each tip of the .01" bucket
;   even when the data logger has been recently restarted.

; Read pyranometer (solar radiation), convert to watts/m^2 and
;   store result at W_m2

1:  Volt (Diff) (P2)
 1: 1        Reps
 2: 22       7.5 mV 60 Hz Rejection Range
 3: 3        DIFF Channel
 4: 23       Loc [ W_m2      ]
 5: 200      Mult
 6: 0        Offset

; Set negative values to zero

2:  If (X<=>F) (P89)
 1: 23       X Loc [ W_m2      ]
 2: 4        <
 3: 0        F
 4: 30       Then Do

3:  Z=F (P30)
 1: 0        F
 2: 0        Exponent of 10
 3: 23       Z Loc [ W_m2      ]

4:  End (P95)

; Count switch closures of rainfall tipping bucket, convert
;   to inches of rain during this execution cycle, and store
;   result at RAIN
```

```
5:  Pulse (P3)
 1: 1        Reps
 2: 2        Pulse Channel 2
 3: 2        Switch Closure, All Counts
 4: 20       Loc [ RAIN      ]
 5: 0.01     Mult
 6: 0.0      Offset

; Read wind speed sensor, convert to mph, and store at WS_mph

6:  Pulse (P3)
 1: 1        Reps
 2: 1        Pulse Channel 1
 3: 21       Low Level AC, Output Hz
 4: 21       Loc [ WS_mph    ]
 5: 1.677    Mult
 6: 0.4      Offset

; Read wind direction sensor, convert to degrees from north, and
;   store reult at WD_deg

7:  Excite-Delay (SE) (P4)
 1: 1        Reps
 2: 5        2500 mV Slow Range
 3: 3        SE Channel
 4: 2        Excite all reps w/Exchan 2
 5: 2        Delay (units 0.01 sec)
 6: 2500     mV Excitation
 7: 22       Loc [ WD_deg    ]
 8: 0.142    Mult
 9: 0        Offset

; Compute statistics and totals for some weather variables
;   and store results into input storage locations so that
;   they can later be sent to the moisture data logger

; If on a 15 minute interval, then set the output flag high
;    to enable storing results in input storage area

8:  If time is (P92)
 1: 0        Minutes (Seconds --) into a
 2: 15       Interval (same units as above)
 3: 10       Set Output Flag High (Flag 0)

; Average all solar radiation readings and store the result
;   at Sun_W_m2

9:  Set Active Storage Area (P80)
 1: 3        Input Storage Area
 2: 4        Loc [ SUN_W_m2  ]

10:  Average (P71)
 1: 1        Reps
```

```
 2: 23       Loc [ W_m2      ]

; Compute the net wind vector and the average wind speed.
;   Store the average wind speed at WIND_ave and store the
;   net wind vector direction at WIND_dir

11:  Set Active Storage Area (P80)
 1: 3        Input Storage Area
 2: 5        Loc [ WIND_ave  ]

12:  Wind Vector (P69)
 1: 1        Reps
 2: 0        Samples per Sub-Interval
 3: 01       S, é1 Polar
 4: 21       Wind Speed/East Loc [ WS_mph    ]
 5: 22       Wind Direction/North Loc [ WD_deg    ]

; Compute the maximum wind velocity and store at WIND_max

13:  Set Active Storage Area (P80)
 1: 3        Input Storage Area
 2: 7        Loc [ WIND_max  ]

14:  Maximum (P73)
 1: 1        Reps
 2: 0        Value Only
 3: 21       Loc [ WS_mph    ]

; Total all rainfall for 15 minute interval and store at
;   RAIN_tot

15:  Set Active Storage Area (P80)
 1: 3        Input Storage Area
 2: 8        Loc [ RAIN_tot  ]

16:  Totalize (P72)
 1: 1        Reps
 2: 20       Loc [ RAIN      ]

; Set port 1 high one minute prior to sampling the following
;   sensors.  Port 1 controls the switched 12 volts, which applies
;   power to some sensors.  The T & H sensors must be powered at
;   least one second prior to taking a reading.  One minute is
;   more than ample to allow all powered sensors to stabilize
;   before measurement.

17:  If time is (P92)
 1: 14       Minutes (Seconds --) into a
 2: 15       Interval (same units as above)
 3: 30       Then Do

18:  Do (P86)
 1: 41       Set Port 1 High
```

```
19:  End (P95)

; Sample the remaining sensors at 15 minute interval and then
;   send all weather data to final storage and to the moisture
;   data logger

20:  If time is (P92)
 1: 0        Minutes (Seconds --) into a
 2: 15       Interval (same units as above)
 3: 30       Then Do

; Read barometric pressure and store at P_mb

21:  Volt (Diff) (P2)
 1: 1        Reps
 2: 24       2500 mV 60 Hz Rejection Range
 3: 6        DIFF Channel
 4: 24       Loc [ P_mb      ]
 5: 1.84     Mult
 6: 600      Offset

; Convert barometeric pressure to mmHg

22:  Z=X*F (P37)
 1: 24       X Loc [ P_mb      ]
 2: 0.75006  F
 3: 3        Z Loc [ P_mmHg    ]

; Read air temperature (deg. C) and store at T_C

23:  Volt (SE) (P1)
 1: 1        Reps
 2: 5        2500 mV Slow Range
 3: 2        SE Channel
 4: 1        Loc [ T_C       ]
 5: 0.1      Mult
 6: -40      Offset

; Read relative humidity and store at RH

24:  Volt (SE) (P1)
 1: 1        Reps
 2: 5        2500 mV Slow Range
 3: 1        SE Channel
 4: 2        Loc [ RH        ]
 5: 0.1      Mult
 6: 0        Offset

; Limit the maximum relative humidity to 100%

25:  If (X<=>F) (P89)
 1: 2        X Loc [ RH        ]
 2: 3        >=
 3: 100      F
```

```
 4: 30       Then Do

26:  Z=F (P30)
 1: 100      F
 2: 0        Exponent of 10
 3: 2        Z Loc [ RH        ]

27:  End (P95)

; Set control port 1 low to remove power from some sensors

28:  Do (P86)
 1: 51       Set Port 1 Low

; Read the battery voltage and store at BATT_W

29:  Batt Voltage (P10)
 1: 9        Loc [ BATT_W    ]

; Store present date/time and weather data in final storage

30:  Set Active Storage Area (P80)
 1: 01       Final Storage Area 1
 2: 1        Array ID

31:  Real Time (P77)
 1: 1110     Year,Day,Hour/Minute (midnight = 0000)

32:  Sample (P70)
 1: 1        Reps
 2: 9        Loc [ BATT_W    ]

33:  Sample (P70)
 1: 1        Reps
 2: 1        Loc [ T_C       ]

34:  Sample (P70)
 1: 1        Reps
 2: 2        Loc [ RH        ]

35:  Sample (P70)
 1: 1        Reps
 2: 3        Loc [ P_mmHg    ]

36:  Sample (P70)
 1: 1        Reps
 2: 4        Loc [ SUN_W_m2  ]

37:  Sample (P70)
 1: 1        Reps
 2: 5        Loc [ WIND_ave  ]

38:  Sample (P70)
 1: 1        Reps
```

```
 2: 6        Loc [ WIND_dir  ]

39:  Sample (P70)
 1: 1        Reps
 2: 7        Loc [ WIND_max  ]

40:  Sample (P70)
 1: 1        Reps
 2: 8        Loc [ RAIN_tot  ]

41:  End (P95)

; At 2:10 a.m. synchronize weather logger time
;    with time from soil moisture logger

42:  If time is (P92)
 1: 130      Minutes (Seconds --) into a
 2: 1440     Interval (same units as above)
 3: 30       Then Do

43:  SDI-12 Recorder (P105)
 1: 0        SDI-12 Address
 2: 0        Start Measurement (aM0!)
 3: 8        Port
 4: 30       Loc [ TIME      ]
 5: 1.0      Mult
 6: 0.0      Offset

; If the moisture logger fails to communicate
;  then -99999 will be stored in "TIME".
;  If communication has failed then do not
;  update the time clock

44:  If (X<=>F) (P89)
 1: 30       X Loc [ TIME      ]
 2: 3        >=
 3: 0        F
 4: 30       Then Do

45:  Set Real Time Clock (P114)
 1: 0        Set Hr,Min,Sec from locations
 2: 30       Loc [ TIME      ]

46:  End (P95)

47:  End (P95)

*Table 2 Program
  02: 0.0000    Execution Interval (seconds)

*Table 3 Subroutines

; Subroutine to send weather data to moisture logger
```

```
1:  Beginning of Subroutine (P85)
 1: 98       Subroutine 98

2:  SDI-12 Sensor (P106)
 1: 0        SDI-12 Address
 2: 0009     Time/Values
 3: 1        Loc [ T_C       ]

3:  End (P95)

End Program

-Input Locations-
1 T_C       5 1 5
2 RH        1 2 2
3 P_mmHg    1 1 1
4 SUN_W_m2  1 1 1
5 WIND_ave  1 1 1
6 WIND_dir  1 1 0
7 WIND_max  1 1 1
8 RAIN_tot  1 1 1
9 BATT_W    1 1 1
10 __________ 1 0 0
11 __________ 1 0 0
12 __________ 1 0 0
13 __________ 1 0 0
14 __________ 1 0 0
15 __________ 1 0 0
16 __________ 1 0 0
17 __________ 0 0 0
18 __________ 0 0 0
19 __________ 0 0 0
20 RAIN      1 1 1
21 WS_mph    1 2 1
22 WD_deg    1 1 1
23 W_m2      1 2 2
24 P_mb      1 1 1
25 __________ 0 0 0
26 __________ 0 0 0
27 __________ 0 0 0
28 __________ 1 0 0
29 __________ 1 0 0
30 TIME      1 2 1
31 __________ 1 1 0
32 __________ 1 1 0
33 __________ 1 0 0
34 __________ 1 0 0
35 __________ 1 0 0
36 __________ 1 0 0
37 __________ 1 0 0
38 __________ 1 0 0
39 __________ 0 0 0
40 __________ 0 0 0
41 __________ 0 0 0
```

```
42 __________ 0 0 0
43 __________ 0 0 0
44 __________ 0 0 0
45 __________ 0 0 0
46 __________ 0 0 0
47 __________ 0 0 0
48 __________ 0 0 0
49 __________ 0 0 0
50 __________ 0 0 0
51 __________ 0 0 0
52 __________ 0 0 0
53 __________ 0 0 0
54 __________ 0 0 0
55 __________ 0 0 0
56 __________ 0 0 0
57 __________ 0 0 0
58 __________ 0 0 0
59 __________ 0 0 0
60 __________ 0 0 0
61 __________ 0 0 0
62 __________ 0 0 0
63 __________ 0 0 0
64 __________ 0 0 0
65 __________ 0 0 0
66 __________ 0 0 0
67 __________ 0 0 0
68 __________ 0 0 0
69 __________ 0 0 0
70 __________ 0 0 0
71 __________ 0 0 0
72 __________ 0 0 0
-Program Security-
0000
0000
0000
-Mode 4-
-Final Storage Area 2-
0
-CR10X ID-
0
-CR10X Power Up-
3
```

ii) Soil Moisture Station Program Code

```
;{CR10X}
;
*Table 1 Program
  01: 5         Execution Interval (seconds)

; Read soil moisture probes every fifteen minutes

1:  If time is (P92)
 1: 0        Minutes (Seconds --) into a
 2: 15       Interval (same units as above)
 3: 30       Then Do

; Set port 1 high to power the probes

2:  Do (P86)
 1: 41       Set Port 1 High

; Wait two execution cycles (10 sec.) for probe
;   electronics to stabilize

3:  Beginning of Loop (P87)
 1: 1        Delay
 2: 2        Loop Count

4:  End (P95)

; Measure the frequency of each CS615 probe and
;   multiply result by .001 to convert to KHz

5:  Pulse (P3)
 1: 1        Reps
 2: 1        Pulse Channel 1
 3: 21       Low Level AC, Output Hz
 4: 25       Loc [ FREQ_CS1  ]
 5: .001     Mult
 6: 0        Offset

6:  Pulse (P3)
 1: 1        Reps
 2: 2        Pulse Channel 2
 3: 21       Low Level AC, Output Hz
 4: 26       Loc [ FREQ_CS2  ]
 5: .001     Mult
 6: 0        Offset

; Remove power from probes to save battery

7:  Do (P86)
 1: 51       Set Port 1 Low

; Convert probe1 fequency to period (msec.)
```

```
8:  Z=1/X (P42)
 1: 25       X Loc [ FREQ_CS1  ]
 2: 27       Z Loc [ PER_CS1   ]

; Insert period of probe1 into polynomial which
;   calculates soil water content

9:  Polynomial (P55)
 1: 1        Reps
 2: 27       X Loc [ PER_CS1   ]
 3: 23       F(X) Loc [ SM_CS1    ]
 4: -.187    C0
 5: .037     C1
 6: .335     C2
 7: 0        C3
 8: 0        C4
 9: 0        C5

; Convert probe2 fequency to period (msec.)

10:  Z=1/X (P42)
 1: 26       X Loc [ FREQ_CS2  ]
 2: 28       Z Loc [ PER_CS2   ]

; Insert period of probe2 into polynomial which
;   calculates soil water content

11:  Polynomial (P55)
 1: 1        Reps
 2: 28       X Loc [ PER_CS2   ]
 3: 24       F(X) Loc [ SM_CS2    ]
 4: -.187    C0
 5: .037     C1
 6: .335     C2
 7: 0        C3
 8: 0        C4
 9: 0        C5

; Take readings from all EC-5 probes and apply
;   factory calibration equation.  For multiple
;   EC-5 probes, increase the "Reps" in the
;   following instruction.

12:  Excite-Delay (SE) (P4)
 1: 6        Reps
 2: 5        2500 mV Slow Range
 3: 1        SE Channel
 4: 1        Excite all reps w/Exchan 1
 5: 1        Delay (units 0.01 sec)
 6: 2500     mV Excitation
 7: 11       Loc [ SM1       ]
 8: 1        Mult
 9: 0        Offset
```

```
;take readings from four tensiometer


13:  Ex-Del-Diff (P8)
 1: 3        Reps
 2: 4        250 mV Slow Range
 3: 4        DIFF Channel
 4: 1        Excite all reps w/Exchan 1
 5: 1        Delay (units 0.01 sec)
 6: 2500     mV Excitation
 7: 43       Loc [ TENSIO    ]
 8: -2.12    Mult
 9: 0.0      Offset

; Read the battery voltage and store at BATT_SM

14:  Batt Voltage (P10)
 1: 10       Loc [ BATT_SM   ]

; Read current date/time and store in input storage
;   starting at year

15:  Time (P18)
 1: 3        Store Year,Day,Hr,Min,Sec in 5 consecutive locations
 2: 0        Mod/By
 3: 30       Loc [ year      ]

; Multiply hour by 100 to move over two places and then add
;   minutes to hour to get four digit time format

16:  Z=X*F (P37)
 1: 32       X Loc [ hr        ]
 2: 100      F
 3: 35       Z Loc [ hr_min    ]

17:  Z=X+Y (P33)
 1: 35       X Loc [ hr_min    ]
 2: 33       Y Loc [ min       ]
 3: 35       Z Loc [ hr_min    ]

18:  End (P95)

; Wait one minute for collection of weather data
;   to be completed and then receive weather data
;   from weather logger

19:  If time is (P92)
 1: 1        Minutes (Seconds --) into a
 2: 15       Interval (same units as above)
 3: 30       Then Do

20:  SDI-12 Recorder (P105)
 1: 0        SDI-12 Address
```

```
 2: 0        Start Measurement (aM0!)
 3: 8        Port
 4: 1        Loc [ T_C       ]
 5: 1.0      Mult
 6: 0.0      Offset

21:  End (P95)

; Wait an additional minute before storing all
;   data in final storage.  Any time discrepancies
;   between the two loggers is easily accomodated
;   by this timing.

22:  If time is (P92)
 1: 2        Minutes (Seconds --) into a
 2: 15       Interval (same units as above)
 3: 30       Then Do

; Store date/time, battery voltages, weather data
;   and soil moisture data in final storage

23:  Do (P86)
 1: 10       Set Output Flag High (Flag 0)

24:  Set Active Storage Area (P80)
 1: 01       Final Storage Area 1
 2: 1        Array ID

; Store year, day in final storage - two reps for
;   two consecutive locations

25:  Sample (P70)
 1: 2        Reps
 2: 30       Loc [ year      ]

; Store hour/minute in final storage

26:  Sample (P70)
 1: 1        Reps
 2: 35       Loc [ hr_min    ]

; Store all of the remaining data

27:  Sample (P70)
 1: 1        Reps
 2: 9        Loc [ BATT_WTHR ]

28:  Sample (P70)
 1: 1        Reps
 2: 10       Loc [ BATT_SM   ]

29:  Sample (P70)
 1: 1        Reps
 2: 1        Loc [ T_C       ]
```

```
30:  Sample (P70)
 1: 1        Reps
 2: 2        Loc [ RH        ]

31:  Sample (P70)
 1: 1        Reps
 2: 3        Loc [ P_mmHg    ]

32:  Sample (P70)
 1: 1        Reps
 2: 4        Loc [ SUN_W_m2  ]

33:  Sample (P70)
 1: 1        Reps
 2: 5        Loc [ WIND_ave  ]

34:  Sample (P70)
 1: 1        Reps
 2: 6        Loc [ WIND_dir  ]

35:  Sample (P70)
 1: 1        Reps
 2: 7        Loc [ WIND_max  ]

36:  Sample (P70)
 1: 1        Reps
 2: 8        Loc [ RAIN_tot  ]

; Set the "Reps" in the following instruction
;  equal to the number of EC-5 probes used

37:  Sample (P70)
 1: 6        Reps
 2: 11       Loc [ SM1       ]

; Do two reps to store both CS615 readings

38:  Sample (P70)
 1: 2        Reps
 2: 23       Loc [ SM_CS1    ]

; Also store the periods for each CS615 to
;   enable recalibration if needed

39:  Sample (P70)
 1: 2        Reps
 2: 27       Loc [ PER_CS1   ]

40:  Sample (P70)
 1: 3        Reps
 2: 43       Loc [ TENSIO    ]

41:  End (P95) ;
```

```
*Table 2 Program
  02: 0.0000    Execution Interval (seconds)


*Table 3 Subroutines

; Send current time (hr, min, sec) to weather logger
;   (Note: the weather logger invokes this subroutine
;   via P105 "SDI-12 Recorder" command.  This is done
;   at 2:10 a.m.)

1:  Beginning of Subroutine (P85)
 1: 98       Subroutine 98

2:  SDI-12 Sensor (P106)
 1: 0        SDI-12 Address
 2: 0503     Time/Values
 3: 32       Loc [ hr        ]

; Put current date and time into input locations
;    year, day_of_yr, hr, min, sec

3:  Time (P18)
 1: 3        Store Year,Day,Hr,Min,Sec in 5 consecutive locations
 2: 0        Mod/By
 3: 30       Loc [ year      ]

4:  End (P95)

End Program

-Input Locations-
1 T_C       5 1 5
2 RH        1 1 0
3 P_mmHg    1 1 0
4 SUN_W_m2  1 1 0
5 WIND_ave  1 1 0
6 WIND_dir  1 1 0
7 WIND_max  1 1 0
8 RAIN_tot  1 1 0
9 BATT_WTHR 1 1 0
10 BATT_SM   1 1 1
11 SM1       5 1 1
12 SM2       9 1 1
13 SM3       9 1 1
14 SM4       9 1 1
15 SM5       9 1 1
16 SM6       17 1 1
17 SM7       1 0 0
18 SM8       1 0 0
19 SM9       1 0 0
20 SM10      1 0 0
```

```
21 SM11      1 0 0
22 SM12      0 0 0
23 SM_CS1    1 1 1
24 SM_CS2    1 0 1
25 FREQ_CS1  1 1 1
26 FREQ_CS2  1 1 1
27 PER_CS1   1 2 1
28 PER_CS2   1 1 1
29 ______    1 0 0
30 year      5 1 2
31 day_of_yr 9 1 2
32 hr        25 1 3
33 min       9 1 2
34 sec       17 0 2
35 hr_min    5 2 2
36 _________ 1 0 0
37 _________ 1 0 0
38 _________ 1 0 0
39 _________ 1 0 0
40 _________ 1 0 0
41 _________ 0 0 0
42 RX_error  1 0 0
43 TENSIO    5 1 1
44 TENSIO_2  9 0 1
45 TENSIO_3  17 0 1
46 TENSIO_4  1 0 0
-Program Security-
0000
0000
0000
-Mode 4-
-Final Storage Area 2-
0
-CR10X ID-
0
-CR10X Power Up-
3
```

APPENDIX B

CRBASIC PROGRAM CODE FOR DP_WS

Weather Station Program Code

```
'Program name: C:\PC208W\CR10X_Programs\WTHRSDI.CR1
'Date written: 5/12/2008
'Transform Version: 0.5
'Transform file: C:\Program Files\Campbellsci\LoggerNet\CR10X.TRN
Version: 1.1
'
'This program was converted from C:\PC208W\CR10X_Programs\WTHRSDI.CSI
'using Campbell Scientific's Transformer application.
'
'CRBasic angle units are in Radians by default.
'Switch to Degrees as CR10 used Degrees.
 AngleDegrees
'
' Declare array of flags as the CR10 had.
Public Flag(8) as boolean

'{CR10X}
' This program stores the time and all weather data in final
'   storage every fifteen minutes.  Rainfall is totaled for
'   the entire 15 minute interval.  The wind vector instruction
'   is used to store average wind speed and direction.  Also,
'   maximum wind speed is computed and stored.  Weather data are
'   transferred to the soil moisture data logger every fifteen
'   minutes, one minute after it is collected.  The time clock
'   of the weather logger is synchronized to that of the soil
'   moisture logger at 2:10 a.m. every morning.  The soil moisture
'   logger time is updated via cell modem once a day at 2:05 a.m.

'\\\\\\\\\\\\\\\\\\\\\\\\\ DECLARATIONS ////////////////////////

Public T_C
Public RH
Public P_mmHg
Public SUN_W_m2
Public WIND_aveArray(15)
Public RAIN
Public WS_mph
Public WD_deg
Public W_m2
Public P_mb
Public TIME

Public SUN_W_m2Array(15)
'Public WIND_aveArray(15)
Public WIND_maxArray(15)
Public RAIN_totArray(15)

Alias WIND_aveArray(2)=WIND_ave
Alias WIND_aveArray(3)=WIND_dir
Alias WIND_aveArray(4)=WIND_max
Alias WIND_aveArray(5)=RAIN_tot
```

```
Alias WIND_aveArray(6)=BATT_W


'\\\\\\\\\\\\\\\\\\\\\\\\ OUTPUT SECTION ////////////////////////

DataTable(Table1,true,-1)
  OpenInterval
  DataInterval(0,15,Min,10)
  Average(1, W_m2, FP2, 0)
  WindVector(1, WS_mph, WD_deg, FP2, 0, 0, 0, 1)
  Maximum(1, WS_mph, FP2, 0, False)
  Totalize(1, RAIN_tot, FP2, 0)
  Sample(1, BATT_W, FP2)
  Sample(1, T_C, FP2)
  Sample(1, RH, FP2)
  Sample(1, P_mmHg, FP2)
  Sample(1, SUN_W_m2, FP2)
  Sample(1, WIND_ave, FP2)
  Sample(1, WIND_dir, FP2)
  Sample(1, WIND_max, FP2)
  Sample(1, RAIN_tot, FP2)
EndTable

'\\\\\\\\\\\\\\\\\\\\\\\\ SUBROUTINES ////////////////////////

Sub Subroutine98
' Subroutine to send weather data to moisture logger
      'P106
    EndSub


'\\\\\\\\\\\\\\\\\\\\\\\\ PROGRAM ////////////////////////

BeginProg

  Scan(10,Sec, 3, 0)
' The following instructions are executed at each execution cycle
'   to allow averaging over the 15 minute output period and, in
'   the case of rainfall, to detect each tip of the .01" bucket
'   even when the data logger has been recently restarted.
' Read pyranometer (solar radiation), convert to watts/m^2 and
'   store result at W_m2
    VoltDiff(W_m2, 1, mV7_5, 3, true, 0, _60Hz, 200, 0)
' Set negative values to zero
    If (W_m2 < 0) Then
      W_m2 = 0
    EndIf
' Count switch closures of rainfall tipping bucket, convert
'   to inches of rain during this execution cycle, and store
'   result at RAIN
    PulseCount(RAIN_tot, 1, 2, 2, 0, 0.01, 0)
' Read wind speed sensor, convert to mph, and store at WS_mph
    PulseCount(WS_mph, 1, 1, 1, 1, 1.677, 0.4)
' Read wind direction sensor, convert to degrees from north, and
```

```
'   store reult at WD_deg
    BRHalf(WD_deg, 1, mV2500, 3, VX2, 1, 2500, False, 20000, 250, 355,
0)
' Compute statistics and totals for some weather variables
'   and store results into input storage locations so that
'   they can later be sent to the moisture data logger
' If on a 15 minute interval, then set the output flag high
'    to enable storing results in input storage area
    CallTable Table1
' Average all solar radiation readings and store the result
'   at Sun_W_m2
    If (Table1.output(1,1)=true) Then GetRecord(SUN_W_m2Array,Table1,1)
' Compute the net wind vector and the average wind speed.
'   Store the average wind speed at WIND_ave and store the
'   net wind vector direction at WIND_dir
    If (Table1.output(1,1)=true) Then GetRecord(WIND_aveArray,Table1,1)
' Compute the maximum wind velocity and store at WIND_max
    If (Table1.output(1,1)=true) Then GetRecord(WIND_maxArray,Table1,1)
' Total all rainfall for 15 minute interval and store at
'   RAIN_tot
    If (Table1.output(1,1)=true) Then GetRecord(RAIN_totArray,Table1,1)
' Set port 1 high one minute prior to sampling the following
'   sensors.  Port 1 controls the switched 12 volts, which applies
'   power to some sensors.  The T & H sensors must be powered at
'   least one second prior to taking a reading.  One minute is
'   more than ample to allow all powered sensors to stabilize
'   before measurement.
    If  TimeInToInterval(14,15,Min) Then
      PortSet(1, 1)
    EndIf
' Sample the remaining sensors at 15 minute interval and then
'   send all weather data to final storage and to the moisture
'   data logger
    If  TimeInToInterval(0,15,Min) Then
' Read barometric pressure and store at P_mb
      VoltDiff(P_mb, 1, mV2500, 6, true, 0, _60Hz, 1.84, 600)
' Convert barometeric pressure to mmHg
      P_mmHg = P_mb * 0.7501
' Read air temperature (deg. C) and store at T_C
      VoltSE(T_C, 1, mV2500, 2, False, 0, 250, 0.1, -40)
' Read relative humidity and store at RH
      VoltSE(RH, 1, mV2500, 1, False, 0, 250, 0.1, 0)
' Limit the maximum relative humidity to 100%
      If (RH >= 100) Then
        RH = 100
      EndIf
' Set control port 1 low to remove power from some sensors
      PortSet(1, 0)
' Read the battery voltage and store at BATT_W
      Battery(BATT_W)
' Store present date/time and weather data in final storage
    EndIf
' At 2:10 a.m. synchronize weather logger time
'    with time from soil moisture logger
```

```
    If  TimeInToInterval(130,1440,Min) Then
      SDI12Recorder(TIME, 7, "0", "M!", 1, 0)
' If the moisture logger fails to communicate
'  then -99999 will be stored in "TIME".
'  If communication has failed then do not
'  update the time clock
      If (TIME >= 0) Then
        'P114
      EndIf
    EndIf
  NextScan
EndProg
```

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